Understanding the Potential of CO_2 Utilisation

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To the whole global community of CO_2 Utilisation; it has been inspiring to be part of this community for 11 years. I have enjoyed networking with so many of you through CO2Chem and meeting so many at the ICCDU. It is inspiring to look back over the time frame of this thesis and see how much has been achieved in realising the potential of CO_2 utilisation. However there is still so much to come – keep researching, discussing, collaborating and paving the way for a more sustainable renewable and recycled carbon future.

Abstract

CO_2 utilisation processes can convert CO_2 into commercially viable products such as fine chemicals, polymers, fertilisers, minerals and fuels via a range of chemical and biological pathways. Carbon is ubiquitous within the chemical and construction industry however sustainability issues arise with fossil sources. CO_2 has potential to be a sustainable and circular source of carbon if certain barriers are overcome. Assessment of the potential of CO_2 utilisation is complex and must address the three pillars of sustainability – environment, economics and society. Herewith, each aspect is discussed and elucidated. A framework to encourage the integration of environmental and economic assessment is presented to tackle the challenge of conflicting conclusions from individual assessments. This is further developed in to a triple helix approach by the addition of social impact assessment. This approach enhances effective decision making for development and deployment by enabling trade-offs between environmental, economic and social impacts to be explored. The challenges and opportunities of small and medium enterprises (SMEs) are considered. Barriers to the general success of SMEs are identified in the fields of policy/regulation, life cycle analysis studies, financial knowledge, and external links. Communication of CO_2 utilisation technologies is investigated as it is known public awareness of CO_2 utilisation is low and is key to successful deployment. Guidelines for communication and the first CO_2 utilisation App presented. Significant increases in knowledge of CO_2-derived products were observed after use of the App. Within the focus groups the App was highly rated for learning, ease of use, learning and enjoyment, confirming it as fit for purpose as a tool to communicate CO_2 utilisation opportunities. CO_2 utilisation has many facets which are interwoven and require unlocking for its potential to be realised. This works seeks to expound these facets to increase understanding in unlocking that potential.

Contents

Introduction

Carbon Dioxide (CO_2) Utilisation is a technology area that is emerging onto the market. CO_2 utilisation is not simply a technology for greenhouse gas mitigation. It has a varied and wide range of impacts including resource efficiency, industrial symbiosis, creation of a circular economy, job creation and creation of a sustainable process industry. CO_2 has potential to be a sustainable and circular source of carbon if certain barriers are overcome. Understanding the potential of CO_2 utilisation requires that a comprehensive and holistic view of the interactions between technological, economic, environmental and societal aspects is taken. However, discourse and frameworks to assess these interlinkages are often lacking within CO_2 utilisation.

This work seeks to explore these facets by applying a triple helix approach, Figure A. By developing insights into the interlinkages between the pillars of sustainability this work offers new frameworks and guidance for considering the potential of CO_2 utilisation in a holistic manner. Furthermore, novel approaches to communication of CO_2 utilisation technologies are presented in the form of Top Trump cards and the first CO_2 utilisation App.

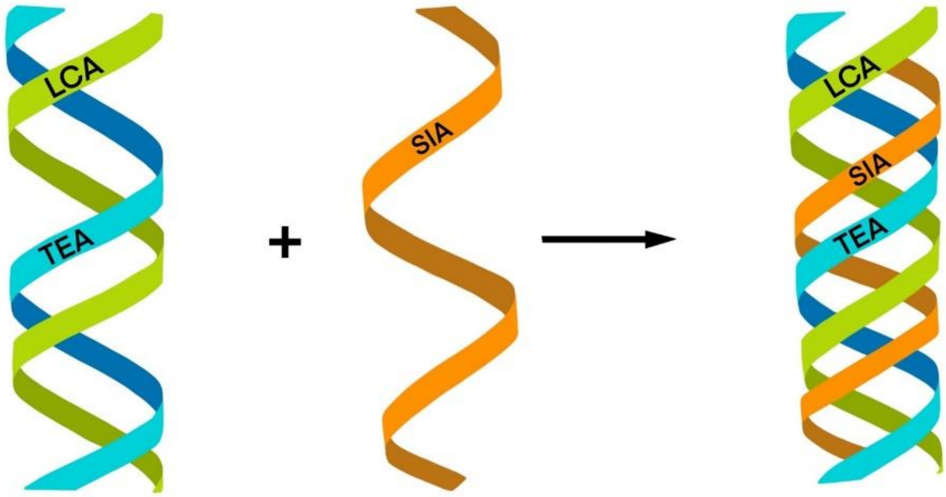

Figure A. Combining life cycle (LCA) and techno-economic assessment (TEA) with social impact assessment (SIA) to create a tripe helix. Produced by K. Armstrong published in McCord *et al.*, 2021

This thesis is the product of over eight years of research and engagement within the CO_2 utilisation community as a part time PhD student under a staff PhD. Subsequently, a hybrid approach is taken to this thesis. It is presented as a mix of published research papers (Chapters 5,6 and 7), other original published works (Chapters 3,4 and 9) and additional material to support the aims and narrative flow. A short summary is presented at the start of each chapter to guide the reader. To aid the flow of the work, bibliographies are presented at the end of each chapter and supporting information for the research papers and additional supporting published papers by the author related to chapter 10 can be found at the end of the thesis in the Supplementary Material section.

Chapters 1 and 2 provide the reader with a broad background to the field of CO_2 utilisation, setting the scene for the thesis. Chapter 1 explores possible motivations for deploying CO_2 utilisation technologies, discussing the role of CO_2 in climate change and the rational for the use of CO_2 as a carbon feedstock. Conclusions are drawn that CO_2 utilisation is multifaceted approach. It should not be regarded purely as a mitigation technology but also considered for its role in creating a sustainable circular economy and for renewable energy storage. Chapter 2 discusses different CO_2 utilisation technologies and provides the reader an appreciation of the depth of the field and the range of possible CO_2-derived products. Furthermore, Chapter 2 examines the link between carbon capture and storage (CCS) and CO_2 utilisation, concluding although related through their use of CO_2 they should be considered as complementary technologies as they have differing goals. Terminology used within CO_2 utilisation is also discussed as numerous terms are used within the field which can be confusing to stakeholders. The chapter ends with an introduction to the growth of CO_2 utilisation introducing some perceived barriers which are later explored in Chapter 8.

All CO_2 utilisation technologies require a source of CO_2, therefore no discussion on the potential of CO_2 utilisation can be complete without a discussion on carbon capture and sources. Chapter 3 investigates possible point sources of CO_2 within Europe. This chapter was written early in the research period and uses data from the 2014 European Pollutant Release and Transfer Register (E-PRTR). Furthermore, sources of CO_2 are linked to their proximity to industrial clusters for identification of symbiotic opportunities within the circular economy.

For CO_2 utilisation to reach its potential, technologies must move through technology readiness levels (TRLs) from research to pilot scale to full industrial deployment. Chapter 4 explores some of these emerging industrial applications particularly exploring early technology adopters that have been deployed in the production of polymers and mineral carbonates. The chapter also highlights funding mechanisms that have been instrumental in deployment and the barriers faced. Topics that are explored deeper in subsequent chapters.

When discussing CO_2 utilisation with stakeholders frequently questions are raised regarding the relationship between CO_2 utilisation, carbon capture and storage (CCS) and enhanced hydrocarbon/oil (EHR) recovery and the possible scale of CO_2 utilisation. The research paper presented in Chapter 5 addresses these issues. The paper concludes that CO_2 utilisation should be considered as a mitigation technology alongside CCS. Regarding EHR, the paper discusses how EHR can lead to net GHG emissions when considering the whole life cycle and it a time when fossil fuels use should be reduced, low carbon CO_2 utilisation fuels should be considered instead. The topic of avoid carbon emissions is introduced with a theoretically discussion on how this could lead to an overall decrease in total emissions when considering the whole system. A cradle to gate scenario for CO_2 utilisation deployment is presented whereby by using renewable energy for production, in an optimistic, challenging scenario for CO_2 utilisation could utilise 1.3 GT CO_2 by 2030.

Frameworks for assessment methodologies are presented in the next two chapters (6 and 7). As technologies will never reach deployment unless they are environmentally, economically and socially viable. These published research papers explore the necessity for integrating different assessment types to highlight conflicting conclusions from individual assessments. Chapter 6 considers the integration of multiple assessments using the example of integrating life cycle assessment and techno-economic assessment. The paper recognises that a 'onesize fits all' methodology for integration does not suit the varying goals of diverse stakeholders. Therefore, a methodology framework for determining the approach to be taken based on the purpose (goal), TRL and resource availability is proposed. All integrated assessments rely on subordinate studies to feed the inventories of the integrated study. Life cycle analysis and techno-economic analysis are well defined and guidelines for their application to CO_2 utilisation have been presented (Zimmermann *et al.*, 2018). Conversely, methodological guidance for assessing social impacts is missing in the field of CO_2 utilisation. This prevents, preventing the triple helix of sustainability assessment (environmental, economic and social impacts) from being completed (Figure A). Chapter 7 therefore, presents the first paper to explore the application of social impact assessment in CO_2 utilisation. Considering social impacts ensures no inadvertent harm to humans is caused by CO_2 utilisation deployment. The paper explores the subject of social impact assessment (SIA) noting that this is different from social acceptance (which is discussed later in chapters 9 and 10). A methodology for screening potential social impacts for emerging CO_2 utilisation technologies is presented and demonstrated enabling potential hotspots to highlighted and addressed. The methodology enables 3-way integration through the proposed triple helix approach enabling trade-offs between environmental, economic and social impacts to be explored. This triple helix enhances effective decision making for understanding the potential of development and deployment of CO_2 utilisation technologies.

As previously discussed in chapter 4, all new technologies progress through technology readiness levels (TRLs) from research to deployment. It is well documented that technologies can struggle to overcome the so called 'valley of death ', where technologies need increasing levels of funding to progress through development stages from TRL 4-6. Barriers to the general success of SMEs have been identified in literature in the areas of policy/regulation, LCA studies, financial knowledge, and external links. In Chapter 8, a survey of companies within the CO_2 utilisation sector is undertaken comparing results between small and medium sized enterprises (SME's) and larger enterprises. This study aimed to elucidated if reported barriers are applicable to the CO2 utilisation sector and to recommend approaches to tackle these barriers.

Chapters 9 and 10 conclude the work by discussing communication of CO_2 utilisation. For products derived from CO_2 to thrive in the market, they will be required to have beneficial environmental impacts, be economically viable, cause no additional social impacts and ultimately the consumer must be willing to buy the product. Public perception and acceptance of an emerging technology is known to be an essential component to viability. Limited research in this field for CO_2 utilisation products exists. As CO_2 utilisation technologies are complex, stakeholders often have a lack of awareness of CO_2 utilisation's potential applications. Therefore, communication strategies for CO_2 utilisation need careful development - the same communication strategy cannot be employed for diverse stakeholder groups. Chapter 9 comprises of a published book chapter outlining strategies for communication within CO_2 utilisation. Some of these strategies are then demonstrated in Chapter 10 where the application of gamification is explored to convey the positive and negative aspects of the sector.

The interdependence of environmental, economic and social impacts (the triple helix) is key to realisation of potential of CO_2 utilisation. All three must be assessed and integrated methodologies are advantageous, this work presents approaches to achieve this. Effective communication CO_2 utilisation and the triple helix of impacts are likewise essential. Herewith, an overview of CO_2 utilisation, along with novel approaches and frameworks are presented to enable the reader to avoid pitfalls and increase awareness and understanding of the potential for CO_2 utilisation.

McCord, S., Armstrong, K. and Styring, P. (2021) 'Developing a Triple Helix Approach for CO2 Utilisation Assessment', *Faraday Discussions*. doi: 10.1039/d1fd00002k.

Zimmermann, A. W., Wunderlich, J., Buchner, G. A., Müller, L., Armstrong, K., Michailos, S., Marxen, A. and Naims, H. (2018) *Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO2 Utilization*. doi: 10.3998/2027.42/145436.

Declaration

I, the author, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not been previously been presented for an award at this, or any other, university.

Publications arising from this thesis are as listed:

Chapter 3: This chapter was original published as part of the Horizon 2020 CarbonNext project, SPIRE5; GA no: 723678 www.carbonnext.eu and later part was translated into German as a published chapter in CO_2 und CO – Nachhaltige Kohlenstoffquellen für die Kreislaufwirtschaft, Springer Spektrum, 20201F.

Chapter 4: This chapter comprises of a reprint of a book chapter published by the author in the McCord, S., Armstrong, K. and Styring, P. (2021) 'Developing a Triple Helix Approach for CO2 Utilisation Assessment', *Faraday Discussions*. doi: 10.1039/d1fd00002k.

Chapter 5: This chapter comprises of a reprint of a research paper by McCord, S., Armstrong, K. and Styring, P. (2021) 'Developing a Triple Helix Approach for CO2 Utilisation Assessment', *Faraday Discussions*. doi: 10.1039/d1fd00002k.

Chapter 6: This chapter comprises of a reprint of a research paper by McCord, S., Armstrong, K. and Styring, P. (2021) 'Developing a Triple Helix Approach for CO2 Utilisation Assessment', *Faraday Discussions*. doi: 10.1039/d1fd00002k.

Chapter 7: This chapter comprises of a reprint of a research paper by McCord, S., Armstrong, K. and Styring, P. (2021) 'Developing a Triple Helix Approach for CO2 Utilisation Assessment', *Faraday Discussions*. doi: 10.1039/d1fd00002k.

Chapter 9: The work contained in this chapter was part of the Horizon 2020 CarbonNext project, SPIRE5; GA no: 723678 www.carbonnext.eu and subsequently published as a chapter in North, M. and Styring, P. (eds) (2019) *Carbon Dioxide Utilization: From Fundamentals to Production Processes*. De Gruyter.

An introduction at the start of each chapter containing published work explains the authors contribution to the work. Further publications by the author used as supporting work can be found in the Supplementary Material.

Abbreviations

CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CDU	Carbon Dioxide Utilisation
CCS	Carbon Capture and Storage
DAC	Direct Air Capture
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
PtoL	Power to Liquid
PtoG	Power to Gas
PtoX	Power to X (gas/liquid)
SIA	Social Impact Assessment
SLCA	Social Life Cycle Assessment
SME	Small and Medium Enterprise
TEA	Techno-Economic Assessment
TRL	Technology Readiness Level

1 The motivation for CO_2 utilisation

1.1 Introduction

Carbon Dioxide (CO_2) utilisation uses the carbon atom in CO_2 molecules as a carbon feedstock to create new products, thus reducing the need for obtaining carbon from fossil sources. By using carbon dioxide as a carbon source, new opportunities are created which can lower environmental impacts, increase resource efficiency, promote a circular economy, increase sustainability and encourage growth through new opportunities (Styring *et al.*, 2011; Wilson *et al.*, 2015; Mission Innovation, 2017; European Commission, 2018b).

CO_2 utilisation processes can convert CO_2 into commercially viable products such as fine chemicals, polymers, fertilisers, minerals and fuels via a range of chemical and biological pathways (Aresta, 2010; Peters *et al.*, 2011; Styring *et al.*, 2011). Carbon-based products are ubiquitous and essential in many aspects of modern life. By creating new production routes from CO_2, fossil-carbon-free materials can be created. There are a number of reasons as to why CO_2 utilisation is a technology of increasing interested for the implementation of a circular economy. The desire to use CO_2 as a carbon source has been increasing in recent years due to increasing demands for environmentally advantageous processes which do not use fossil sources of carbon. Although bio-based carbon sources can meet some carbon demands, bio-sources are limited and broad range of carbon sources will be necessary to fulfil demand (European Commission, 2018b).

1.2 Carbon Dioxide and Climate Impacts

Carbon Dioxide (CO_2) is formed from one atom of carbon covalently bonded to two atoms of oxygen and is naturally occurring in our atmosphere. It is a necessary part of the carbon cycle where plants use CO_2, light and water to create carbohydrate energy and oxygen. Carbon dioxide is an emitted by-product of combustion and chemical processes and produced biogenic sources. As our energy requirements increase due to global urbanisation and other factors, amounts of CO_2 in atmosphere are increasing (Intergovernmental Panel on Climate Change, 2014). CO_2 accounts for 80% of greenhouse gases (US EPA, 2018) and causes warming of our atmosphere.

Carbon dioxide has a linear structure with three vibrational modes; an asymmetric stretch, a symmetric stretch and a bend. The asymmetric stretch and bend are infrared active and it is this that causes CO_2 to act as a greenhouse gas. The CO_2 adsorbs and re-emits some of the infrared radiation which is created when visible light hits the Earth, trapping it in the atmosphere and causing a warming effect. CO_2 and other greenhouse gases (GHGs) in the atmosphere are necessary to keep the Earth at a temperature to sustain life, but increasing accumulations of GHGs are extremely likely to have led to an increased global warming effect (Intergovernmental Panel on Climate Change (IPCC), 2014; IPCC, 2018).

CO_2 concentrations in the atmosphere have been rising since the industrial revolution, reaching a global peak level of 400ppm for the first time in May 2013 at the National Oceanic and Atmospheric Administration's (NOAA) Mauna Loa Observatory in Hawaii. By September 2016, the value remained consistently above 400ppm (Figure 1.1). 400ppm is seen as a substantial milestone in the rise in global CO_2 levels. CO_2 levels continuously fluctuate in the atmosphere both seasonally due to plant growth and over numerous years during warming periods. The range of CO_2 levels over the last 800,000 years has been found to be between 180-280ppm. At the start of the industrial revolution in the 19th century CO_2 levels were around 280ppm, but have since been rapidly increasing due to the release of CO_2 into the atmosphere from the combustion of fossil fuels, leading to concerns that CO_2 emissions must be decreased to avoid climate change (Thomas *et al.*, 2004).

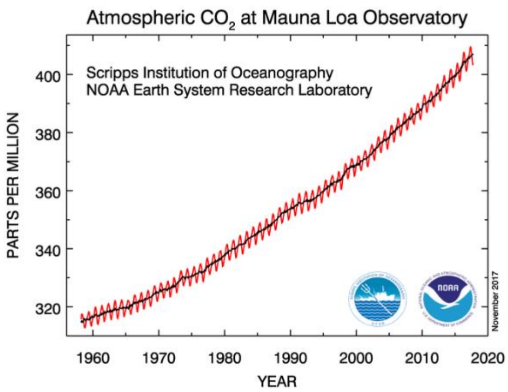

Figure 1.1. Monthly mean atmospheric carbon dioxide at Mauna Loa Observatory, Hawaii.(https://www.esrl.noaa.gov)

The United Nations, (1992) defined climate change as:

> "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods."

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted at the Rio Earth Summit. Countries joined this international treaty to cooperatively work to tackle climate changes by focusing on limiting global temperature rises. The Convention came into force on 21 March 1994 with counties who have ratified the Convention becoming 'Parties to the Convention'. Further steps to define emission reduction targets were implemented via the Kyoto Protocol in 1997 (UNFCCC, 1998) with a final ratification in 2005. The Kyoto Protocol brought about two emission reduction commitment periods 2008-2012 followed by 2013 to 2020. Each with legally binding targets. With each agreement goals became increasingly ambitious. The latest agreement, The Paris Agreement was negotiated at the 21st Conference of Parties (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC) in December 2015. The agreement between 196 parties seeks to achieve the following aims:

> (a) Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
> (b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and
> (c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development. (UNFCCC, 2015)

By October 2016, 168 of the original UNFCCC parities signed the agreement, each party agreeing to increase their commitment to reduce CO_2 emissions and the consequences of climate change. Each country committed to regularly reporting its emissions and steps they are taking to implement reductions via nationally determined contributions (NDCs). There are several mechanisms to do this. Sceneario modelling by the International Energy Agency gives a number of mitigation options which are combined to reach the necessary targets (International Energy Agency, 2014). These include increasing renewable energy capacity, efficency measures, expansion of nuclear energy generation and fitting carbon capture and storage units to existing emitters. These must be deployed in increasing capacity to curb emissions and Figure 1.2 shows the IEA's model to achieve this. Another approach is to dramatically curtail the use of fossil fuels, rapidly switching energy production to low-carbon sources. (McGlade *et al.*, 2014) state that to give at least a 50% chance in a lower than 2^oC rise, over 80% of global currient coal reserves, 50% of gas reserves and 33% of oil reserves must not be used. Both of these approaches are ambious and will necessitate a step-chance in technology and policy comittment to achieve them.

In 2014 the IPCC stated that if current trends of greenhouse gas emissions are followed it is predicted that global temperatures will rise by between 3.7^oC and 4.8^oC above pre-industrial levels by 2100 (Intergovernmental Panel on Climate Change (IPCC), 2014). In order to give at least a 50% chance of achieving the below 2^OC warming target, it was calculated that cumulative global CO_2 emissions need to be limited to 1100 GT between 2010 and 2050 (Meinshausen *et al.*, 2009; Intergovernmental Panel on Climate Change, 2014); necessitating a reduction of CO_2 emissions of just under 40 GT by 2050. However, the 2018 IPPC report on 'Global Warming of 1.5°C' concludes that risks are higher at 2°C warming than 1.5°C. If current trends are followed, 1.5°C of warming is likely to be reached between 2030 -2052. Warming of 1.5°C creates risks to health, livelihoods, food security, water supply, human security and economic growth which are further exasibated if warming increases to 2°C (IPCC, 2018). To limit warming to 1.5°C net CO_2 emissions need to be reduced by 45% of 2010 levels by 2030, and be net zero by 2050. Achieving these goals requires a rapid transition to a low carbon emission economy.

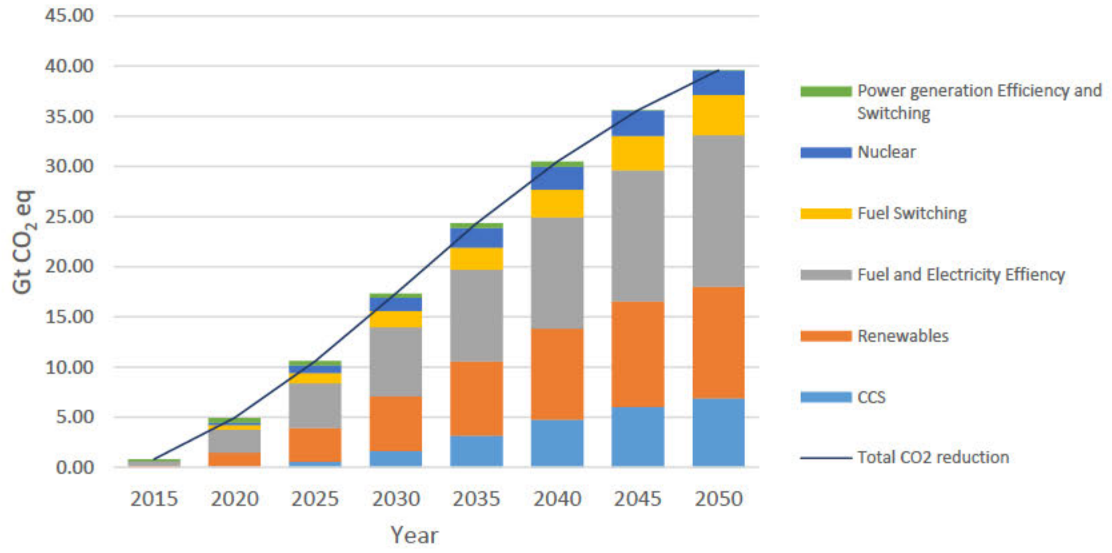

Figure 1.2 World CO_2 reduction targets to meet the 2 °C scenario (2ds) (adapted from IEA 2014)

1.2.1.1 GHG emissions in the UK

The UK established a legally binding target to reduce greenhouse gas emission in the Climate Change Act in 2008 (Parliament of the United Kingdom, 2008). This compels the UK to reduce its emissions of CO_2 NO_x and CH_4 by at least 80% of the 1990 levels by 2050. The Act is carried out through a series of carbon budgets (Table 1-1) each set for a 5 year period of time, progressively increasing the level of reductions. The UK has met the first two carbon budgets and it on track to meet the third, however there are concerns that the plans are not sufficient to meet the 4th or 5th budgets or the new target of net zero emissions by 2050 set in 2019 (Committee on Climate Change, 2019).

Table 1-1 UK Carbon Budget, adapted from Parliament of the United Kingdom, 2008; UK, 2011; BEIS, 2019

	1st Carbon Budget 2008-2012	2nd Carbon Budget 2013-2017	3rd Carbon Budget 2018-2022	4th Carbon Budget 2023-2027	5th Carbon Budget 2028-2032
Carbon budget level (million tonnes CO_2 equivalent ($MtCO_2e$))	3018	2782	2544	1950	1725
Percentage reduction below base year levels	23%	29%	35%	50%	56%
Actual emissions ($MtCO_2e$)	2954	2504	887 (2018-19)		

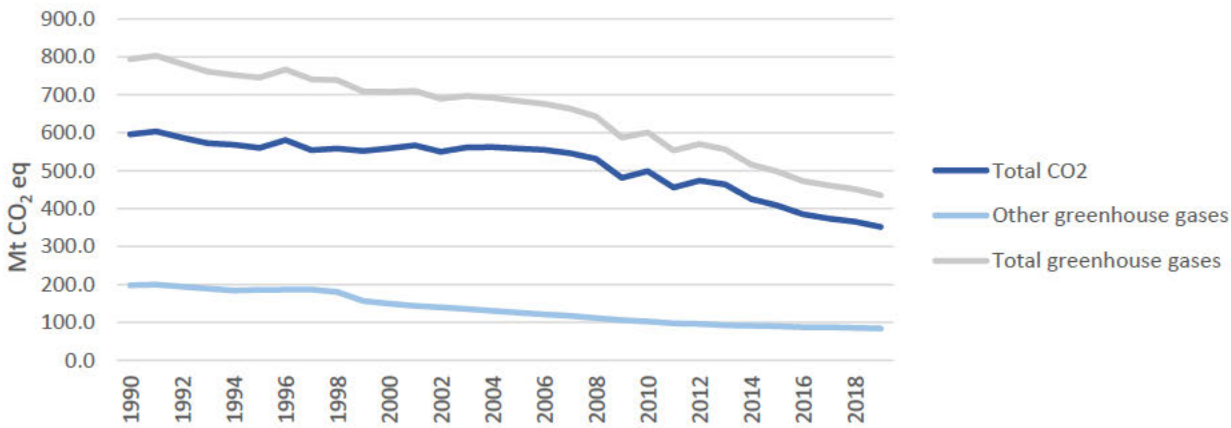

Figure 1.3 UK greenhouse gas emissions, 1990-2019 (provisional) (BEIS, 2019)

In 1990, the UK emitted 580.5 million tonnes of carbon dioxide, making up 76% of the UK's greenhouse gas emissions (BEIS, 2019). Encouragingly, GHG emissions in the UK are slowly declining since the Climate Change Act (Figure 1.3) reaching a low of 352 Mt CO_2 in 2019. However, this decline must be expedited to meet reduction targets. CO_2 emissions from the energy sector have historically been the greatest contributor to GHG emissions in the UK, until energy emissions were overtaken by the transport sector in 2016, Figure 1.4. Energy supply emissions have sharply fallen due to the increase in low carbon renewable energy from wind and solar and the closure of coal power generation (Committee on Climate Change, 2019). Emissions from Industry have been falling since 1999 with increased efforts to reduce industrial emissions including the aim of creating the world's first net-zero carbon industrial cluster by 2040. However significant changes such as deploying carbon capture and storage (CCS) have not occurred due to the lack of ongoing financial support. The UK CCUS (Carbon Capture, Utilisation and Storage) Action Plan was published in November 2018 looking to accelerate such technologies (Committee on Climate Change, 2019).

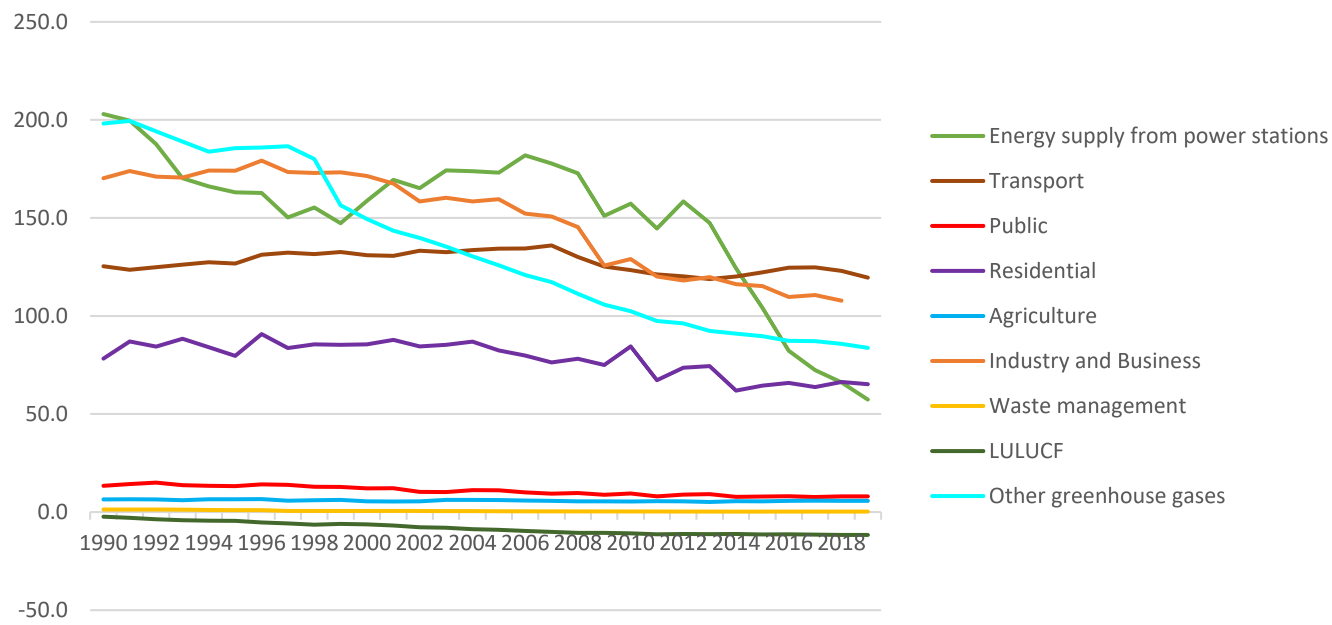

Figure 1.4 UK Annual territorial greenhouse gas emissions by source 1990-2019 (provisional). (BEIS, 2019)

1.3 CO_2 as a carbon source

The chemical and petrochemical sectors are large industrial consumers of oil and gas. In 2017, they consumed 14% of the total primary oil and 8% of total primary gas demand, resulting in contributions 1.25GT of direct CO_2 emissions a 2% growth from 2016 (IEA, 2019). The origin of 90% of all organic chemicals is fossil carbon, themselves using 5-10% of the global consumption of crude oil (Wilson *et al.*, 2015). To meet emission reduction targets and create a sustainable chemical industry decoupling from fossil carbon both for energy generation and as a feedstock could significantly reduce environmental impacts. Finding alternative, sustainable sources of carbon to supply the chemical and process industries presents both interesting opportunities and challenges (Bazzanella *et al.*, 2017). Alternative sources include biomass, recycling wastes, marine and CO and CO_2. Using CO_2 as a source of carbon has been identified as a technology that could be deployed in conjunction with others to reach the goal of a sustainable, low carbon impact chemicals sector (Wilson *et al.*, 2015; Mission Innovation, 2017; European Commission, 2018b; Gabrielli *et al.*, 2020).

There are three overarching factors which contribute to the motivation for CO_2 utilisation (
Figure 1.5):

- as a carbon mitigation technology including as an additional stage to carbon capture and storage (CCS), that may add some economic benefit to CCS
- an alternative sustainable carbon source for production of chemicals

- a method of converting renewable electrical energy into a storable chemical form (production of CO_2-based fuels)

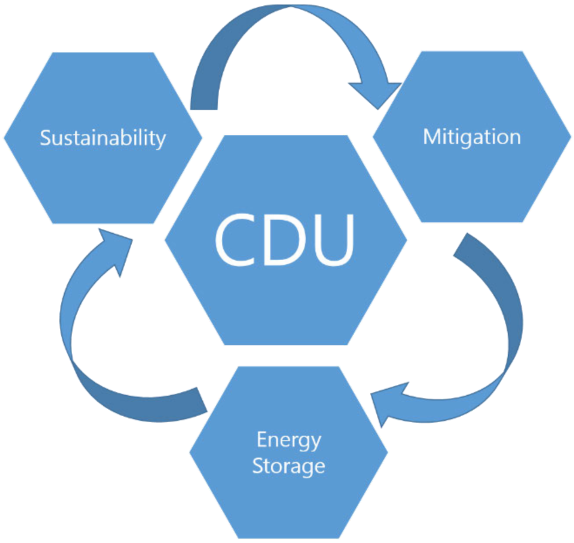

Figure 1.5 Motivation for CO_2 utilisation triad

In each CO_2 utilisation technology, a balance between the three triad aspects will occur. In some cases, such as the production of fuels, the amount of renewable energy used and the net CO_2 avoided will be reasonably high however the long term mitigation aspect can be viewed as lower due to the short sequestration time of the CO_2. Conversely when CO_2 is used in a mineralisation process, a long sequestration time is obtained but no renewable energy is stored. For each CO_2 utilisation application there are pros and cons for each aspect of the triad. Therefore, it is problematic to compare different processes and assess which is the 'superior' application of CO_2 utilisation technologies as a whole. As such CO_2 utilisation technologies should ideally be compared using functionality i.e. fuel a plane, create a net-zero emission chemical with other options such as bio-based technologies. Hence the comparitive question should be: what is the function I am wishing to achieve and what is the 'best' method to achieve it causing the least environmental, econiomic and social impact? By adopoting this approach the potential market opportunities and carbon footprint reductions of a CO_2 utilisation product can be ascertained.

1.3.1 Climate change mitigation as motivation for CO_2 Utilisation

The mitigation prospects of CO_2 utilisation are often the most highly debated aspect, especially when CO_2 utilisation is compared with other high capacity CO_2 mitigation technologies such as carbon capture and storage (CCS) (Mac Dowell *et al.*, 2017). CO_2 mitigation in relation to CO_2 utilisation not only encompasses the long and short-term sequestration of CO_2, but can take into account any emissions decrease via switching from traditional production to the CO_2 utilisation process; often called CO_2 avoided and emissions created in the process. This is more complex to assess than purely the CO_2 utilised in production and therefore requires a comprehensive life cycle assessment (LCA) throughout the supply chain (von der Assen *et al.*, 2014). Although CO_2 utilisation can contribute to overall emissions reductions targets, it must be part of a much wider mitigation strategy encompassing a variety of different technologies and approaches (Quadrelli *et al.*, 2014) including decarbonising electricity production

The impact that CO_2 utilisation can have on climate change via the reduction of CO_2 emissions is a much debated subject. A number of studies (Table 1-2) have been carried out that indicate a range of amounts of CO_2 that could be utilized. Each study has predicted amounts based on a number of assumptions and scenarios, but it is important to note that these amounts are for the CO_2 that could be utilised not the CO_2 emissions that are avoiding release to the atmosphere. In reality some CO_2 will be released in the production and the studies do not take into account the amounts of renewable energy necessary to reach these levels. For the studies predicting higher amounts of CO_2 used a large proportion is used to make hydrocarbons for use as synthetic fuels or in the chemical industry and in these cases large amounts of energy will be needed.

Table 1-2 Predicted amounts of CO_2 that can be utilised

Amount of CO_2 used	Year study published	Author	Note
300 MT/y	2013	Aresta *et al.*	Prediction for 2016
Up to 1.5 Gt/y	2011	Centi *et al.*,	
Up to 2Gt/y	2009	Dechema *et al.*	
1.5Gt/y	2015	Armstrong and Styring	Based on a scenario of products
7 Gt/y by 2030	2016	Global CO2 Initative	By 2030 for a number of key products

1.3.2 Sustainability as motivation for CO_2 utilisation

The move towards a carbon-constrained economy necessitates the desire to find alternative sources of carbon for process and chemical industries (CarbonNext, 2018). Sustainability in the chemical industry has been defined by OECD (Organisation for Economic Co-operation and Development) as:

".... a scientific concept that seeks to improve the efficiency with which natural resources are used to meet human needs for chemical products and services. Sustainable chemistry encompasses the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes."

Therefore, strong arguments exist for switching to using CO_2 as a feedstock if it displaces the use of hazardous chemicals e.g. phosgene in the production of aromatic polycarbonates (Chapter, 13, Styring *et al.*, 2014) and for exploring CO_2 as a carbon source for the chemical industry. Sustainable chemistry approaches have a number of benefits including avoiding the used of hazardous materials, increasing the use of renewable resources whilst simultaneously decreasing the use of non-renewable resources and minimising environmental impacts of the chemical industry while seeking to manufacture products that are economically competitive. However, they are not without challenges.

Carbon for the chemical industry has typically been primarily obtain from petroleum sources, but increased awareness regarding environmental impacts and sustainability have led to the need to look to sources such as biomass, CO_2 or wastes. As CO_2 is an abundant C1 source it is a key target when considered as an alternative carbon feedstock. CarbonNext (CarbonNext, 2018) studied alternative sources of carbon, although this study excluded biological and marine sources, it was concluded that CO_2 and CO provided a good alternative carbon supply in Europe, whilst other sources such as shale gas, coal-bed methane and heavy oil had low potential due to resource quantity and environmental concerns.

CO_2 utilisation has the potential to increase industrial symbiosis opportunities within the sector by valorising CO_2 and utilising other wastes or by-products (European Commission, 2018a). In industrial symbiosis, unwanted material, energy, water, by-products & waste residues from one process are re-purposed as a feedstock or energy supply for another process (Chertow, 2000; Mirata, 2004). Developing new industrial symbiotic routes increases sustainability by decreasing waste production unlocking unexploited waste streams are resources (European Commission, 2018b) .

Corporate sustainability strategies can plan a role in the uptake of CO_2 utilisation. The United Nations Sustainable Development Goals (United Nations, 2015) were adopted by the UN member states in 2015. The goals (Figure 1.6) provide a framework for the UN's 2030 sustainable development agenda (*Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs*, 2015) to create peace and prosperity for future of the planet and people. The Sustainable Development Goals (SDGs) each contain specific targets and can be thematically grouped into areas such as water, energy, transport and climate. The goals and targets apply globally but rely on intervention and action on a regional and local scale but a wide range of stakeholders (Salvia *et al.*, 2019). The KPMG Survey of Corporate Responsibility Reporting 2017 surveyed the top 100 companies by revenue in 49 countries. Of these 75% reported on corporate responsibly, with KMPG observing trends in reporting against the SDGs and climate reduction targets. KPMG predict that reporting against SDG's will be an increasing trend, with 39% of organisations already reporting against SDGs less than two years after their launch. In 2017, 67% of the world's largest 250 companies released targets to cut GHG emissions, an increase from 58% in 2015. Primarily this is attributed to increased public and corporate awareness and pressure since the adoption of the Paris Agreement in 2015. Considering the CO_2 utilisation technologies have potential to deliver contributions to several SDG areas (Olfe-kräutlein, 2020) and carbon reduction targets, CO_2 utilisation can have a role to play in sustainability strategies. In regard to the SDGs, of particular interest is how CO_2 utilisation could contribute to the transition to low-carbon renewable energy in SDG7, options in SDG 9 for industrial symbiosis and resource efficiency, creation of building materials from minerals and wastes in SDG 11, contributions to ensuring sustainable use of resources in SDG 12 and through climate change mitigation in SDG 13.

Figure 1.6 The Sustainable Development Goals. Source: United Nations

1.3.3 Energy storage as motivation for CO_2 utilisation

The storage of renewable energy (RE) is key in the transition to a low-carbon energy production future. The intermittence of weather-dependent renewable energy from wind and solar, requires the ability to store created energy so that it can be used in times of demand (Ibrahim *et al.*, 2008; Olah *et al.*, 2009; Wilson *et al.*, 2010, 2017; Varone *et al.*, 2015; Ould Amrouche *et al.*, 2016). Traditionally energy has been stored in a chemical form (fossil fuels) enabling production to match demand. The intermittent nature of renewable energy sources such as solar and wind power does not provide such system flexibility. Therefore, as we transition to a greater proportion of our energy requirements originating from renewable sources the ability to store energy to match demand increases. Renewable energy can be stored in chemical, electrochemical (battery) mechanical, electrical or thermal forms (Ould Amrouche *et al.*, 2016). Chemical storage is seen as advantageous (Wilson *et al.*, 2017) as it has the potential to allow large scale, seasonal storage of energy as is shown in Figure 1.7. Synthetic fuels from CO_2 have significant advantages for intermittent energy storage due to the low costs involved with storage, transportation and handling. In a future where TWhs of energy storage are need CO_2 fuels present an interesting option.

CO_2 fuels could play a role beyond the provision of storage of weather-dependent energy for grid balancing for example for low carbon transport, maritime and aviation purposes (Jiang *et al.*, 2010; Pearson *et al.*, 2012; Cuéllar-Franca *et al.*, 2019). Use of CO_2-derived transportation fuels could remove reliance on fossil-carbon resources and be useful in sectors where transport electrification is not suitable (Scientific Advice Mechanism, 2018). If this is to be realised significant increases in cheap renewable energy production will be needed (Graves *et al.*, 2011; Kätelhön *et al.*, 2019).

In the case of CO_2 utilisation, the transformation of electricity to chemical energy is commonly known as Power to X (PtoX or P2X), where X is either a gas or liquid hydrocarbon. The simplest conversion uses CO_2 combined with renewable hydrogen into produce synthetic natural gas (methane). Here the advantage being that the produced gas could be directly mixed with fossil natural gas in the domestic grid (Olah *et al.*, 2009). The limiting factor in main CO_2 fuels applications is the source of cheap green hydrogen (Royal Society, 2017).

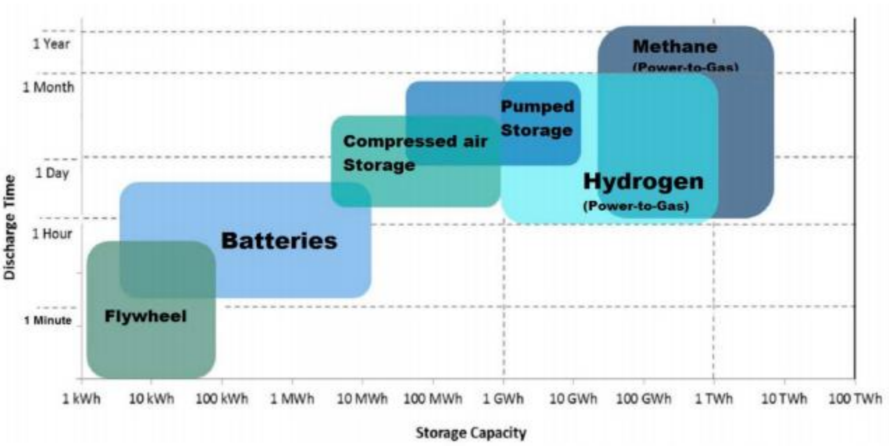

Figure 1.7 Time duration of energy storage options. Source: School of Engineering, RMIT University 2015

1.4 Conclusions

The motivation for CO_2 utilisation is broad and encompasses many aspects. CO_2 utilisation should not be considered as purely a climate change mitigation option, but within many aspects of creating sustainable circular economy. However, interest in CO_2 utilisation has increased as awareness surrounding climate change has amplified and technologies advanced. Although the aim of reducing CO_2 emissions has been a primary driver it should always be clarified via comprehensive life cycle analysis to ensure benefits. Nevertheless, if achieving large CO_2 emission reductions is the sole focus other positive aspects may be discounted, such as the role CO_2-derived fuels can play in energy storage and sustainable transportation. Here, developments in other aspects of GHG emission mitigation such as large scale renewable energy deployment have created symbiotic opportunities with CDU to solve challenges of intermittency and demand. Moreover, requirements for organisations to report their sustainability measures and carbon footprint has led to interest in industrial symbiosis and reuse of wastes whereby CO_2 utilisation can play a role. Decision-making regarding the potential of CO_2 utilization is therefore multi-faceted and not 'one-size fits all'. This work will seek to explore how different motivations interact, the complexities of bringing CO_2 utilisation technologies to market and factors involved in ensuring sustainable and successful deployment.

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2 CO_2 Utilisation Technologies

2.1 Introduction

CO_2 utilisation technologies cover a wide array of products and routes to make them. Carbon is ubiquitous within the chemical industry and the potential arises for CO_2 to become the source of that carbon. However, there are many challenges and barriers to this. Here, CO_2 utilisation and its links to carbon capture and storage are discussed, along with the terminology currently used to describe CO_2 utilisation technologies. Furthermore, common products are discussed with challenges and potential environmental impacts. Finally, barriers to CO_2 utilisation are laid out which will be further explored throughout this work.

2.2 CO_2 utilisation

Carbon dioxide utilisation (CO_2 utilisation) processes convert CO_2 into commercially viable products such as fine chemicals, polymers, fertilisers, minerals and fuels via a range of chemical and biological pathways by exploiting CO_2 as a carbon source (Aresta, 2010; Peters *et al.*, 2011; Styring *et al.*, 2011). The IEA (2019), predict that fuels, chemicals, waste mineralisation, building materials from minerals and biological CO_2 uses could each be scaled to markets in excess of 10 Mt CO_2/yr and can support climate goals.

CO_2 utilisation can be considered as a new synthetic carbon cycle (P. Styring *et al.*, 2014). Within the cycle, CO_2 is used to create a product and then released back to the atmosphere or sequestered in product dependent on the product as shown in Figure 2.1. The length of time the CO_2 is sequestered depends on the lifetime of the product, for products such as fuels the lifetime is short therefore, the CO_2 is quickly re-released, however in the manufacture of materials such as polymers or aggregated the CO_2 can be sequestered for many decades to indefinitely (von der Assen *et al.*, 2014; IEA (International Energy Agency), 2019a). Utilising CO_2 as a carbon feedstock for the chemical industry opens new routes for chemical production that have been previously reliant on fossil oils (Bazzanella *et al.*, 2017). Furthermore, CO_2 utilisation can enable low-carbon energy to be introduced into the chemical supply chain and a circular economy in chemical production to be realised (Styring *et al.*, 2011; Wilson *et al.*, 2015; European Commission, 2018).

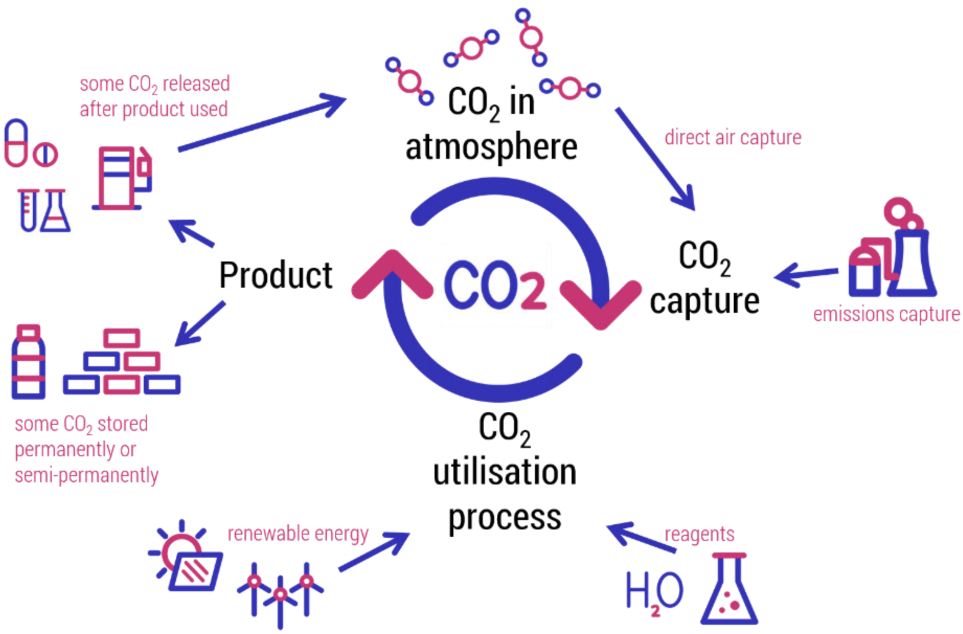

Figure 2.1 Carbon Dioxide Utilisation Cycle. CO2Chem Media and Publishing

2.3 Link between CCS and CO_2 Utilisation

CO_2 utilisation and Carbon Capture and Storage (CCS) are regularly grouped together often as CCUS (Carbon Capture Utilisation and Storage) (Ghinea *et al.*, 2016; BEIS, 2018; IEA (International Energy Agency), 2019b). However, they are two distinct but linked technology pathways both concerning CO_2 emissions (Bruhn *et al.*, 2016). CCS encompasses a range of techniques that capture CO_2 emissions predominately from point sources (e.g. power stations), and transport the CO_2 for sequestration geological formations (Intergovernmental Panel on Climate Change, 2005; IEA (International Energy Agency), 2019a). CCS is recognised by the IEA as a key technology in reducing CO_2 emissions, without which it will be very difficult to reach the a 1.5 or 2 degree scenario (International Energy Agency, 2014; IEAGHG, 2017). CCS can also encompass directly capturing CO_2 from air (known as direct air capture, DAC) and subsequent storage. However, this can incur higher costs than point source capture due to the reduced concentration of CO_2 in air (Fasihi *et al.*, 2019; Lackner *et al.*, 2021)

CO_2 utilisation technologies also capture CO_2 but then transform it by chemical or biological processes into new products of commercial value (Peters *et al.*, 2011; Peter Styring *et al.*, 2014). These products may sequester the CO_2 for long, medium or short time frames depending on the nature and use of the produce, but they also avoid carbon emissions by providing new production routes (von der Assen *et* *al.*, 2013). In comparison to CCS, CO_2 utilisation technologies do not have the same potential capacity to sequester gigatonnes of CO_2 (Mac Dowell *et al.*, 2017). Nevertheless, CO_2 utilisation technologies do present the opportunity to provide new sustainable green routes common chemicals, whilst delivering CO_2 emissions reduction over traditional production methods (Armstrong *et al.*, 2015; Mac Dowell *et al.*, 2017; IEA (International Energy Agency), 2019a).

The direct comparison between CCS and CO_2 utilisation is perhaps inevitable as they both start with the capture of CO_2, but their goals are distinct. For CCS the goal is reducing CO_2 emissions, for CO_2 utilisation using CO_2 as a carbon feedstock for products. Therefore, it is unwise to directly compare them as they have differing aims. However, this has often been the case, with solely the aspect of climate mitigation considered (Mac Dowell *et al.*, 2017). Taking such an approach and ignoring the circular economy and suitability advantages of CO_2 utilisation could lead to misconception regarding the usefulness of CO_2 utilisation.

Although the distinction between the two technologies has been expounded above, it is now becoming increasingly common to refer to carbon capture, utilisation and storage, CCUS. Governments are seeking pathways for the use and sequestration of CO_2 to mitigate emissions and by combining utilisation and storage they seek to analyse the best route for the CO_2 based on volume available, emission purity, location to storage or usage site, industrial symbiosis opportunities and economic opportunities. Examples of this can be seen in the UK (BEIS, 2018), the IEA (IEA (International Energy Agency), 2019b), and the Port of Rotterdam Porthos (*CO2 reduction through storage beneath the North Sea - Porthos*, 2020) project. There are a number of situations that are better suited to storage than utilisation and vice versa, for example if the emitters location has no access to geological storage or if industrial symbiosis opportunities exist locally.

2.4 Terminology to describe CO_2 utilisation

A range of terminology is commonly used to describe the use of CO_2. A search in the literature will find terms such as, CCU – carbon capture and utilisation, CCUS – carbon capture utilisation and storage, CDU – carbon dioxide utilisation, CDC – carbon dioxide conversion and CCR – carbon capture and recycling (or reuse) all used interchangeably and without consistency. Table 2-1 shows a search of both Web of Science and Scopus for commonly used terms. CCUS is most commonly found within a

Scopus search whilst, “carbon dioxide utili*ation” is the most common in Web of Science. This range of terminology used can be confusing to stakeholders.

Table 2-1 Counts of relevant terminology found in Scopus and Web of Science databases, July 2020

Search term	Web of Science	Scopus
CCU and CO2	232	373
CCUS and CO2	323	420
CDU and CO2	35	38
"carbon dioxide utili*ation "	347	325
"carbon capture and utili*ation"	289	332
"carbon dioxide reuse"	8	9
"carbon capture and reuse"	7	9
"carbon dioxide conversion"	297	358
"carbon capture and conversion"	20	23
"carbon dioxide recycling"	49	75
"carbon capture and recycling"	8	8

As observed from the literature search CCU is often used as an abbreviation. Consequently, CCU is often seen as a sub-branch of CCS reliant on CO_2 captured from a power station. CCU and CCS are also often combined to form the all-encompassing descriptor CCUS as described above. In most cases the CO_2 for CO_2 utilisation must first be captured before use, however, this is not always the case for example in mineralisation processes (Hills *et al.*, 2020) or reactive capture (Dowson *et al.*, 2021). Carbon capture is a distinct technology in its own right which can be integrated with CO_2 storage or utilisation. Therefore, for these reasons the term CCU is not always the most appropriate to covey the differences in approach and motivation between storage and utilisation.

Regarding the other terms found in literature, CO_2 Reuse or Recycling (CCR) communicates that the CO_2 has been used in some way first. In many circumstances this is not true; usually the CO_2 is created and emitted from the industrial process, it has not previously been ‘used’, it is in essence a waste product. Therefore, it is technically incorrect terminology to describe it as recycled or reused, however it is recognised that ‘recycling and reuse’ are commonly understood terms and may be useful in non-technical stakeholder discussions (International CCU Assessment Harmonization Group, 2021). If the CO_2 has been captured from the air via direct air capture (DAC), the terms could be applied. However, higher concentration sources of CO_2 are more cost effective (Naims, 2016; CarbonNext, 2018) and therefore likely to be the predominant method applied in the near future. Therefore, although DAC will have a role to play in future CO_2 utilisation scenarios many applications will capture directly emitted rather than atmospheric CO_2 whilst point sources exist, hence CO_2 recycling/reuse is not an accurate term.

The terms CO_2 utilisation, CO. conversion and CO_2 use, infer that CO_2 is used irrespective of its origin or purity. These terms indicate that CO_2 is used to provide some form of useful function, whether that involves using the CO_2 as a discrete species that enters and leaves the system unchanged as in EOR and foodstuffs or as carbon source breaking of carbon-oxygen bonds to transform the carbon dioxide into a new chemical entity. Enhanced Oil Recovery (EOR) though often classified as a CO_2 utilisation technology sits firmly between CCS and CO_2 utilisation. In EOR, CO_2 is used to increase the extraction of fossil oil via increasing pressure and reducing the viscosity of the oil, during which some CO_2 is sequestered (Blunt *et al.*, 1993; Godec *et al.*, 2011) . In this work the CO_2 utilisation is used to describe the transformation of CO_2 into another product via a chemical or biological reaction. As such enhanced oil recovery (EOR) which is commonly described as a CO_2 utilisation technology is not in the scope of the definition of CO_2 utilisation.

As demonstrated in Table 2-1, many different terms are used and a single definition or term for CO_2 utilisation is not presently agreed. Henceforth, in this work the term CO_2 utilisation in preference with CDU as occasional shorthand. Using the term CO_2 utilisation, removes the reference to carbon capture (intrinsically linking it to CCS) and best describes the aim of the technology – to utilize CO_2. The abbreviation CDU is problematic in some geographies due its political use in Germany, therefore should be used with caution and only with other terminology to eliminate confusion. In conclusion, the term CO_2 utilisation is used here to refer to the chemical transformation of CO_2 into a valuable product. Technologies that utilise CO_2 without transformation such as EOR, carbonation of drinks or horticulture are not included. This definition is aligned with Styring et al. (2011, 2014b).

2.5 Using CO_2 as a carbon source

CO_2-derived products can be broadly grouped into three categories; chemicals (bulk chemicals and fine chemicals), fuels and minerals. However, it should be noted that some hydrocarbons can be classified in both the fuels and chemicals groupings, for example methanol can be used both as a bulk chemical feedstock and as a fuel for maritime vessels (Svanberg *et al.*, 2018). Within these groupings further subdivision between chemical and biological synthesis routes can occur. Synthesis of chemicals from CO_2 is not a new technology. Salicylic acid has been synthesised from CO_2 and sodium phenolate via the Kolbe-Schmitt reaction since 1890. Since the early 20th Century, Urea has been produced in a two stage reaction by reacting ammonia produced in the Haber-Bosch process with CO_2 giving (H_2N-(C=O)-NH_2) in an exothermic reaction (Meessen, 2010).

$CO_2 + 2\ NH_3 \rightleftharpoons NH_2COONH_4$

$NH_2COONH_4 \rightleftharpoons CO(NH_2)_2 + H_2O$

This well-established process commonly uses a proportion of the waste CO_2 produced in ammonia production in urea formation, and as such the processes are usually co-located. However, the process still has a significant carbon footprint and therefore, new more environmentally friendly routes to produce urea from CO_2 are currently being researched and developed into pilot production (Driver *et al.*, 2019).

By utilising CO_2 as a carbon source, a vast array of chemicals can be produced. Figure 2.2 demonstrates a number of important chemical transformations of CO_2 that have been reported, whilst new reaction pathways are being developed at an increasing rate. Research is primarily focused on methanol, polymerisations, urea, carboxylates, carbonates and olefins and the discovery of new catalysts and mechanisms for these reactions. Comprehensive reviews on CO_2 utilisation pathways can be found in Aresta, (2010); Peters *et al.*, (2011); Aresta *et al.*, (2014, 2016); and Artz *et al.*, (2017) .

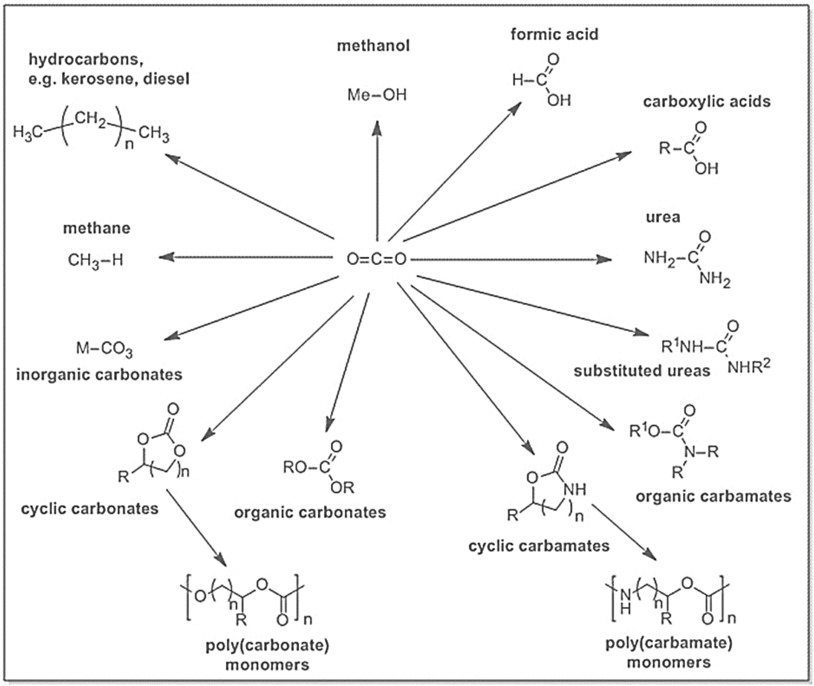

Figure 2.2 A brief overview of chemicals derived from carbon dioxide. Jansen, Styring et al (2011)

Over 90% of organic chemicals are derived from fossil carbon, utilising 5-10% of the global demand of crude oil to manufacture of these products (Wilson *et al.*, 2015), and realising alternative sources of carbon such as CO_2 could reduce this demand but will increase energy demand (Peters *et al.*, 2011; Olfe-Kräutlein *et al.*, 2016; Kätelhön *et al.*, 2019). At the heart of all CO_2 utilisation lies the aim to produce sustainable products with reduced environmental impacts. However, CO_2 utilisation is a diverse field and as discussed in Chapter 1 the further motivation drivers for different categories can differ:

***Chemicals**:* CO_2 utilisation can provide a new source of carbon enabling a routes towards a sustainable process industry which is not reliant of fossil carbon inputs (Bazzanella *et al.*, 2017). Industrial symbiosis can take place whereby one industry's wastes become another's feedstock reducing environmental impacts (Wilson *et al.*, 2015; Patricio *et al.*, 2017; Pieri *et al.*, 2018).

***Fuels**:* CO_2 utilisation offers options to store renewable energy in a chemical form, contributing to the energy transition and decarbonizing the transportation sector via carbon recycling under the right conditions(Olah *et al.*, 2009; Cuéllar-Franca *et al.*, 2019). Energy can be stored for long time periods (seasonally) allowing buffering to occur for intermittent renewable sources (Wilson *et al.*, 2017).

Mineralization*:* CO_2 utilisation can permanently sequester significant quantities of CO_2 in building materials produced by carbonation of mineral wastes creating symbiotic opportunities to valorize waste streams (Hills *et al.*, 2020).

2.6 CO_2 to Chemicals

2.6.1 Bulk Chemicals

Bulk chemicals are used in large quantities in the chemical industry but in general have a low unit price. Many of the products are also used as intermediates (e.g. synthesis gas, methanol, ethanol and formic acid) for subsequent chemical production. Such intermediates are key targets for CO_2 utilisation due to the potential large quantities of CO_2 utilised and the positive repercussion in terms of emissions reduction rippling up the chemical industry supply chain of de-carbonising the base elements (Kätelhön *et al.*, 2019). CO_2 utilisation can also provide environmental advantages by providing less hazardous synthesis routes, for example replacing the use of the highly toxic phosgene (Fukuoka *et al.*, 2010).

Methanol is a key target for CO_2 utilisation due to its use as an intermediate in subsequent chemical reactions and relatively simplicity of conversion (Olah *et al.*, 2009). CO_2 can be hydrogenated in the presence of a wide range of catalysts to form methanol. Synthesis requires three molecules of hydrogen per one molecule of CO_2, two are incorporated into the methanol molecule and the third is used in the production of the by-product, water. Therefore, to ensure minimal GHG emissions from the process, a low-carbon source of hydrogen is necessary, either derived from water electrolysis or steam reformation of methane coupled with CCS (Acar *et al.*, 2014; Pérez-Fortes, Schöneberger, Boulamanti and Tzimas, 2016). In a comparison of fossil methanol production to low carbon CO_2 conversion (Table 2-2) concluded that 34.3 GJ of low carbon electricity (for electrolysis route) would be required for production of one tonne of CO_2-derived methanol but would lead to a negative cradle to gate GHG emission (Bazzanella *et al.*, 2017). Exploiting the potential of low carbon methanol therefore has to be considered in a broader context of national and global renewable energy production (Kätelhön *et al.*, 2019).

Table 2-2 Comparison of Energy Demand and GHG emissions for methanol production routes, Bazzanella et al., 2017

per t methanol	Fossil (SMR+ methanol synthesis)	Low carbon (power to methanol)
Energy feedstock [GJ]	25 –	
Fuel demand [GJ]	13.9 –	
Electricity [GJ]	0.6	34.3
Utilities [GJ]		5.4
Steam balance [GJ]	-2	0
Total energy [GJ]	37.5 (12.5 excl. feedstock)	39.7(41.7 incl. compensation for missing steam export)
Feedstock related CO2 emissions [t]	0.97	-0.79
Process emissions [t]	0.52	0.123
Total emissions [t]	1.49 (1.82 cradle to gate)	-0.67

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, Figure 2.3. Due to the OH (alcohol) group it can be transformed into hydrocarbons, halides, carbonyls, carboxylic acids, amines and ethers. Annual production of methanol reached around 98Mt in 2019 with approximately two-thirds of methanol produced used in the production of other chemicals. Demand is predicted to continue increasing after nearly doubling from 2010 to 2020 (International Renewable Energy Agency (IRENA), 2021). The process of creating methanol from CO_2 is at high TRL (7+) and has reached commercial production in some locations, the main barriers to deployment are unfavourable economic conditions (Pérez-Fortes, Schöneberger, Boulamanti and Tzimas, 2016). Methanol from CO_2 is currently produced in Iceland by Carbon Recycling International (CRI - Carbon Recycling International, 2020). Here, methanol is direct synthesised using industrial flue gases and large scale water electrolysers to produce hydrogen. The gas from the geothermal steam emissions is captured from a geothermal power plant located next to the CRI facility. The plant is powered using combination of hydro, geothermal and wind energy from the Icelandic power grid. 4000 metric ton/year of renewable methanol is currently produced and sold under the Vulcanol brand mainly for use as a fuel additive.

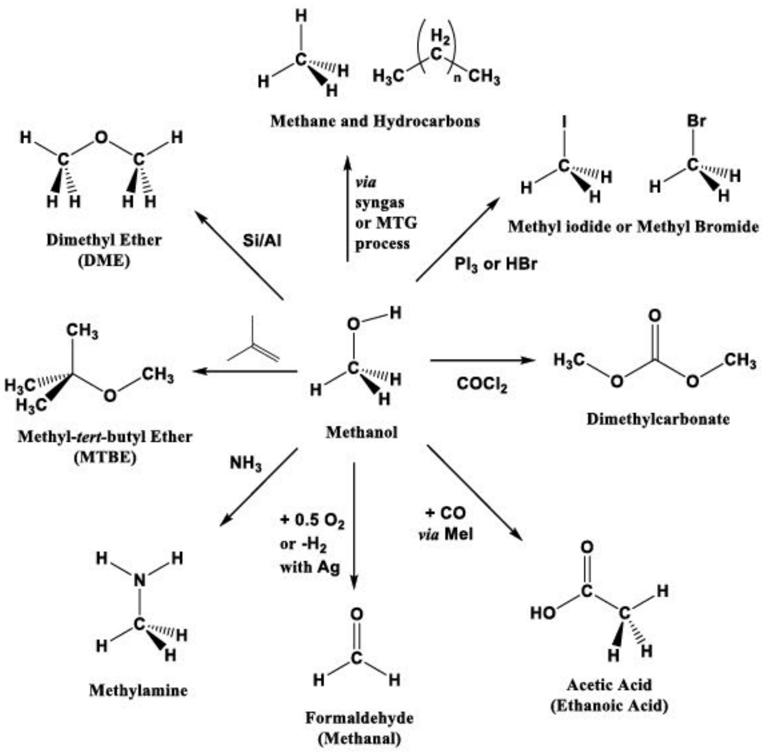

Figure 2.3 A selection of synthetic uses for methanol. Dowson and Styring (2014)

Formic acid can be produced by electrochemical reduction of CO_2 and water rather than the traditional route via CO (Aresta *et al.*, 2016; Pérez-Fortes, Schöneberger, Boulamanti, Harrison, *et al.*, 2016). Formic acid is used as a preservative, adhesive and as a chemical precursor and is also of increasing interest as it can be used as a fuel in fuel cells. The production of formic acid from CO_2 is assessed as being at TRL 3-5 (Pérez-Fortes, Schöneberger, Boulamanti, Harrison, *et al.*, 2016) with a number of start-up companies worldwide looking at the production of formic acid for use as a low carbon energy source including DNV (Norske, 2011). In a comprehensive review and meta-analysis of LCA studies on CO_2 utilisation process, Thonemann, (2020) concluded that CO_2-derived formic acid demonstrated improvements in 11 out of 15 environmental impact categories when compared to conventional production. Specifically, with the use of wind power electricity, a reduction of 95% in global warming impact can be observed concluding this is an encouraging pathway.

2.6.2 Fine/Speciality Chemicals

The reaction between epoxides and CO_2 in the presence of a catalyst gives a highly exothermic reaction as the CO_2 is inserted into the epoxide producing cyclic carbonates (Meléndez *et al.*, 2007; Styring *et al.*, 2014). Cyclic carbonates have been synthesised in this manner since the 1950's and although their production is small at 0.1 Mt per year it is increasingly expanding due to their uses as electrolytes for lithium ion batteries, as solvents and as an intermediate for polymer synthesis. Cost reduction through new catalysts, reactions under atmospheric conditions and synthesis of carbonates directly from flue gas without the need for a capture step, are of particular interest (North *et al.*, 2010, 2011) .

Linear organic carbonates are formed from alcohols and CO_2. They are useful as solvents so have a substantial potential market. The most common of these is Dimethyl carbonate (DMC) is a linear carbonate that is used as a solvent and as a pre-cursor for organic synthesis, in polymer production and as an anti-knocking agent. It can either be produced from CO_2-derived methanol and CO_2 or urea and CO_2. It is traditionally prepared is via highly toxic phosgene and methanol, subsequently producing DMC via CO_2 removes the phosgene reagent giving a safer process. More than 90 000 t/y of DMC is produced globally and has a potential demand of more than 30 Mt/y if used as a fuel additive (Garcia-Herrero *et al.*, 2016). However, meta-analysis by Thonemann, (2020) concludes that the CO_2 utilisation route to DMC can lead to worse environmental impacts.

Polymers are a key target as they have the ability to sequester CO_2 for a substantial time period (Fernández-Dacosta *et al.*, 2017; Royal Society, 2017; Van Heek *et al.*, 2017; Müller *et al.*, 2020). Polymers can be produced by the direct incorporation of the CO_2 molecule into the hydrocarbon chain (Peters *et al.*, 2011). Polyol production incorporating 20 wt% CO_2 has been shown to give a 11-19% reduction in GHG emission (Von Der Assen *et al.*, 2014). In 2016 Covestro opened its first plant to produce precursors for plastics from CO_2 in Dormagen, Germany (Covestro AG, 2021). The plant will produce 5000 tonnes of CO_2-based polyether polyols which will initially be used in the production of flexible memory foams for mattresses and furniture.

2.7 Fuels

Synthetic fuels can be produced from CO_2 and hydrogen often via Fischer-Tropsch reactions to produce long chain hydrocarbons (Aresta *et al.*, 2014, 2016; Fernández-Dacosta *et al.*, 2019). Other routes include biological fermentations and subsequent processing such as the Lanzatech process (Ou *et al.*, 2013; Lanzatech, 2021). Synthetic fuels suitable for a range of applications can be produced but key targets are synthetic diesel, DME and synthetic aviation fuel due to their use in long haul transport applications which are problematic for many other fossil fuel alternatives (Jiang *et al.*, 2010). Energy to produce synthetic fuels must be sourced from renewable or low carbon sources to ensure a fuel with a low carbon footprint is created. Often termed PtoX (X being gas or liquid fuel) there is considerable research interest worldwide in this area though currently the economics and environmental performance are unfavourable (Fernández-Dacosta *et al.*, 2017). CO_2 utilisation may contribute to facilitating the transition to low-carbon renewable energy sources by managing the balance between supply and demand, enabling short and long term seasonal storage of energy resources (Wilson *et al.*, 2010, 2017).

Synthetic methane production is commonly known as Power to Gas (although this term can refer to hydrogen production or methane production from renewable energy). Methane is the main component of natural gas and is used in power generation, heating, as a feedstock for the chemical industry and as a transport fuel. Synthetic methane or synthetic natural gas, can be directly substituted for fossil methane utilising existing infrastructure making it an ideal target (Bazzanella *et al.*, 2017). However, methane production is an energy intensive process requiring low carbon hydrogen (IEA (International Energy Agency), 2019a). Environmental impacts for synthetic methane vary dependent on energy source but can give lower GHG impacts (Thonemann, 2020). Power to Gas is a large research area in Germany with Audi's ETOGas project (Audi, 2020) a demonstration of this.

Dimethyl Ether (DME) is used as a solvent, refrigerant, methylating agent and an oxygenated fuel additive with a global production of around 11 Mt/y. When used as a diesel fuel additive it enables emissions targets to be attained whilst not inhibiting performance. It is relatively easy to produce from CO_2 by either the condensation of CO_2-derived methanol or directly from synthesis gas. Studies have concluded GHG emissions could be reduced between 82%-19% for CO_2-derived DME (Matzen *et al.*, 2016) with most environmental impacts also reduced when using wind energy for production (Thonemann, 2020).

2.8 Minerals

CO_2 can be reacted with minerals, usually calcium or magnesium containing silicates to form carbonates (Styring *et al.*, 2011; IEA (International Energy Agency), 2019a; Hills *et al.*, 2020). These reactions are exothermic therefore do not require large additional energy inputs but give opportunities for energy recovery. Either naturally occurring silicates such as wollastonite (CaSiO3) and olivine (MgSiO4) or industrial waste slags and ashes can be carbonated to produce long term CO_2 storage in marketable form such as fillers, cement or aggregates or use for geological sequestration (Sanna *et al.*, 2014). Potential to decarbonise the concrete industry is also observed when numerous techniques such as bio-energy, CCS, mineral carbonation of wastes are applied (Pedraza *et al.*, 2021; Tanzer *et al.*, 2021).

In-situ Mineral carbonation has occurred in nature over many millions of years, white chalk cliffs are the result of this process(Sanna *et al.*, 2014). Silicate materials containing magnesium or calcium such as serpentine and wollastonite, can undergo accelerated mineralisation which speeds up this geological process by using high pressures and pre-treatments (Hills *et al.*, 2020). Often the minerals must first be mined, ground and processed which contributes to costs and be prohibitive (Leung *et al.*, 2014). Supercritical CO_2 can also be injected into geological formations although this does not result in a commercial product and so is a form of CCS (Snæbjörnsdóttir *et al.*, 2020). Research is being undertaken into the best materials to be carbonates, the effects of particle size (contributing to grinding costs) and the pressure and temperature of CO_2. Companies working in this area include Cambridge Carbon Capture, Solidia, Carbon Free Chemicals and Carbon Cycle.

Industrial wastes can be carbonated resulting in products that can be sold rather than incurring costly disposal tariffs making processes attractive from a circular economy perspective (Renforth *et al.*, 2011; Hills *et al.*, 2020). The wastes need to be alkaline or an alkaline substance introduced to aid the carbonation process. Waste ashes, mining and aggregate wastes and steel slags are particularly suitable for these processes with an estimated 7-17 billion tonnes available annually though these are poorly mapped (Renforth *et al.*, 2011). The mineralisation process is advantageous as numerous contaminants can be stabilised in the product negating the need for end of life treatment of the waste (Hills *et al.*, 2020). These processes are exothermic and hence heat can be recovered and utilised.

Companies working in this area include Carbon 8 (waste ashes), Recoval (steel slags), CCm Research (Cellulosic materials and digestates).

2.9 Growth of CO_2 utilisation

The future prospects for CO_2 utilisation look promising if challenges can be overcome. Numerous reports have discussed the potential of using CO_2 as a carbon source within the chemical industry, for example Mission Innovation, (2017); European Commission, (2018) and IEA (International Energy Agency), (2019) but to realise the potential technologies must be commercialised. Zimmermann *et al.*, (2017a) found that the majority of activities within chemicals and fuels production are at research stage whereas mineralisation technologies are primarily at demonstration. Technology readiness levels can be used to describe the developmental progress of technology from inception to deployment. Originally defined by NASA ((NASA, 2012), TRLs have been further adapted to the chemical industry (Buchner *et al.*, 2018). The SCOT Project (www.scotproject.org) during its research on CO_2 utilisation in Europe assigned TRLs to products, Figure 2.4. It is observed that single products cover wide ranges of TRLs due to the number of different approaches that can be used to make the same product for example – diesel fuels can be made via Fischer-Tropsch processes which are fairly well advanced (TRL 5+) or via photochemical reactions which are less advanced (TRL 1-2).

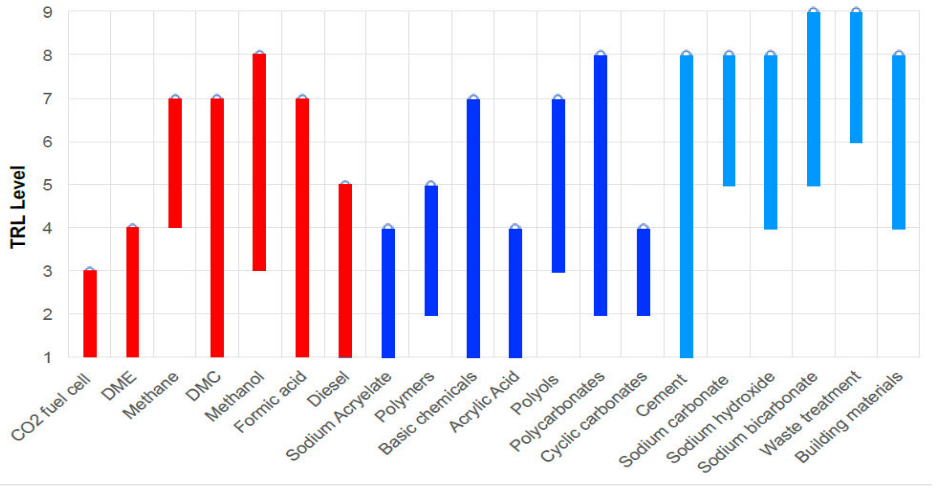

Figure 2.4 Technology readiness of various CO_2 utilisation products (Wilson et al., 2015a). Fuels are coloured red, chemicals and polymers dark blue and carbonates light blue.

Technologies using mineralisation processes (light blue on the figure) are collectively reaching higher TRL levels than those in fuels (red) or chemicals (dark blue) in agreement with Zimmermann *et al.*, (2017a). This is primarily due to the relative simplicity of the reactions and beneficial economics due to cheap reactants and the exothermic reaction meaning heat can be recovered. A major challenge in deployment is how to avoid the 'Valley of Death', the movement from TRL4/5 upwards (Frank *et al.*, 1996; Butler, 2008; Petroski, 2017; Ellwood *et al.*, 2022). This is the place common place technologies fail, moving out from the laboratory into a pilot scale process in an operational environment. At this stage capital investment is heavy and government financing is sort to bridge the gap (Ellwood *et al.*, 2022) .

Identified barriers for the deployment of CO_2 utilisation technologies vary over the short, medium and long term (Figure 2.5). Energy requirements and integration continue to remain a key issue, as energy for CO_2 utilisation and hydrogen production must come from low carbon sources to ensure minimal environmental impacts. Kätelhön et al. (2019), have calculated that 55% of the global energy production in 2030, more than 18 PWh of low carbon energy, would be required to realise the potential of CO_2 utilisation. And herein lies a conundrum for CO_2 utilisation matching the potential to create low carbon chemicals with the vast amount of low-carbon energy that this could require. To reduce the energy requirement the SCOT project (Armstrong *et al.*, 2016) identified key technical research and innovation challenges such as catalysis, reactor design, separation techniques and novel reaction pathways. Accurate assessment of environmental impacts through life cycle analysis (LCA) has been highlighted by many including von der Assen et al., (2013); Armstrong et al., (2016); European Commission, (2018). As it imperative that new CO_2 utilisation technologies do not have an inferior GHG impact than those they are replacing. Though progress has been made through the publication of guidelines (Zimmermann *et al.*, 2018), it is essential to understand the environmental impacts of each CO_2 utilisation process to ensure environmental sustainability and avoid green-washing.

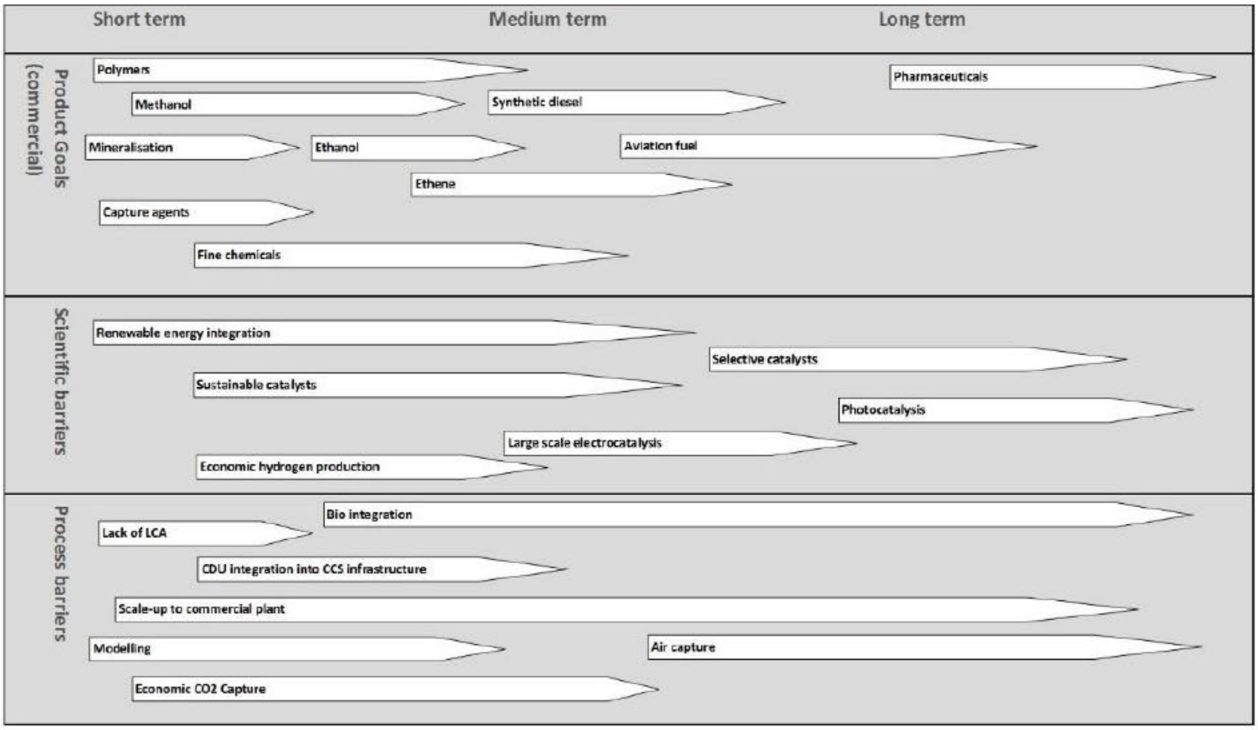

Figure 2.5 Scenarios for implementation of CO_2 utilisation and enabling technologies (created by K Armstrong, published in Quadrelli et al., 2014)

The growth of the CO_2 utilisation market is primarily driven by industry and funding bodies looking for new renewable feedstocks for production in conjunction with searching for methods to reduce emissions (Kant, 2017). Whilst as stated many technologies are in research stage, a number of processes have reached small scale commercial or demonstration phases in the last few years mainly in the fields of mineralisation, fuels and polymers, a snapshot of these is presented Table 2-1. The products that have reached commercialisation in some cases are exploiting specific market factors for example Carbon Recycling International use the abundant geothermal power in Iceland to manufacture methanol and O.C.O Carbon8 Aggregates utilisation waste fly ash and air pollution control residues which attract gate fees for disposal. Reported amounts of CO_2 used or reduced vary across technologies with those in the field of mineralisation commonly reporting the highest reductions. However, it should be noted that details of the exact scope of the emissions analysis are not often reported.

Table 2-3 Selected CO_2 utilisation companies with pilot or production facilities and their stated CO_2 use or reduction

Company	Locations	Product (brand name)	Production per year	CO_2 Used per year or CO_2 reduction	Website reference
Aramco	Saudi Arabia	Polyols (Converge)	Under construction	1/3 carbon footprint	https://www.aramco.com/en/creatingvalue/products/chemicals/converge
Audi	Wertle, Germany	Methane (E-gas)	1000 tons	2800 tons	https://www.audi-technology-portal.de/en/mobility-for-the-future/audi-future-lab-mobility_en/audi-e-gas_en
Carbon Recycling International	Iceland	Methanol (Vulcanol)	4000 tons	5500 tons	http://carbonrecycling.is
Carbonfree Chemicals	San Antonio, USA	Baking soda, bleach, hydrochloric acid	62,000 t HCL 143,000 t Sodium Bicarbonate	75,000 tons (200,000 t avoided)	http://www.carbonfree.cc
CCm Technologies	UK	Fertilizer	13,000 tonnes/yr	90% GHG reduction compared to traditional fertilizer	https://ccmtechnologies.co.uk/
Covestro	Dormagen, Germany	Polyols (cardyon)	5000 tons	Upto 20% emissions reduction	https://solutions.covestro.com/en/brands/cardyon
Fortera	USA	Calcium carbonate cements and cement board	Greater than 700 tons	60% reduction on traditional cement	https://forterausa.com/
Joule Unlimited	New Mexico & Oregon	Solar Fuels		85% GHG emissions reduction	http://www.jouleunlimited.com/
Lanzatech	USA	Ethanol, Jet Fuel	1,500 US gallons of jet fuel	75% emissions reduction compared to petroleum fuel	http://www.lanzatech.com/
O.C.O (formally Carbon8 Aggregates)	Avonmouth and Brandon, UK	Aggregates	150,000 tons	5000 tons	https://oco.co.uk/

2.10 Conclusions

CO_2 utilisation has potential to play a role in the creation of a circular economy. CO_2 could be a sustainable source of carbon for the chemicals and construction industries if certain barriers are overcome. Barriers include technological issues, economic issues and communication issues with stakeholders and the public. Barriers to deployment are not eased by varying terminology used interchangeably to describe CO_2 utilisation and lack of distinction between the goals of CCS and CO_2 utilisation, leading some to discount CO_2 utilisation by only considering the GHG mitigation potential. Despite these barriers, CO_2 utilisation products are reaching the market in niche applications and there is significant observed research interest from major agencies such as the IEA.

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3 Promising CO_2 Point Sources for Utilisation

Content in this chapter was originally part published as part of the EU CarbonNext project [1] www.carbonnext.eu and later part was translated into German as a published chapter in CO_2 und CO – Nachhaltige Kohlenstoffquellen für die Kreislaufwirtschaft, Springer Spektrum, 2020 [2]. Katy Armstrong was the sole author of the original English work, Denis Krämer translated, edited and adapted the work for German publication.

This chapter describes promising point sources of CO_2 within Europe identifying locations and proximity to industrial clusters and therefore potential CO_2 utilisation deployment opportunities. Defining the source of CO_2 is key to CO_2 utilisation technologies, to avoid transporting CO_2 long distances to utilisation sites. By co-locating utilisation technologies with CO_2 sources, symbiotic relationships between industries creating a circular economy can evolve.

[1] CarbonNext EU Horizon 2020 SPIRE5; GA no: 723678

[2] Krämer D., Armstrong K. (2020) CO und CO_2. In: Kircher M., Schwarz T. (eds) CO2 und CO – Nachhaltige Kohlenstoffquellen für die Kreislaufwirtschaft. Springer Spektrum, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-60649-0_2

3.1 Introduction

All CO_2 utilisation technologies require a source of CO_2 as a feedstock. Sources of CO_2 differ in purity, concentration and volume. Therefore, identifying potential sources and matching them with specific CO_2 utilisation technologies can be beneficial. Carbon Dioxide is formed from one atom of carbon covalently double-bonded to two atoms of oxygen and is naturally occurring in our atmosphere. CO_2 is produced in numerous ways including respiration, combustion of organic materials (including fossil fuels) and fermentation. CO_2 is a necessary part of the carbon cycle where plants use CO_2, light and water to create carbohydrate energy and oxygen, however excess CO_2 contributes to global warming.

The carbon molecule in CO_2 can be used as a feedstock to create new valuable carbon-based products. As we move into an increasingly carbon constrained environment, the ability to re-use carbon molecules multiple times could become a key component in the drive to reduce carbon emissions and ensure the sustainability of the chemical industry. The identification of the most promising sources of these carbon emissions enables new and existing industries to identify symbiotic opportunities which could enhance deployment.

Carbon capture aims to capture CO_2 from point sources or from the air using physical or chemical processes so that it can be stored or used. Different sources have different properties which leads to differing ease and cost of capture. CO_2 capture is recognised as a key enabling technology to reduce CO_2 emissions and hence there is a significant depth of research in the field. However, the majority of the research is focused on carbon capture for storage (CCS) not utilisation. In this regard, the volume of CO_2 that can be captured is the key driver, so that these emissions can be significantly sequestered. Hence, large scale emitters such as power stations which individually can emit in excess of 20 Mt CO_2/yr. have been a key research focus (Intergovernmental Panel on Climate Change, 2005). CO_2 utilisation however has different priorities. The quantity of CO_2 that can be utilised varies between different applications. Therefore, a variety of sources can be used depending on the specific application. In general, processes that produce fuels require the most CO_2 but also have the largest energy demand, whereas processes to produce pharmaceuticals and fine chemicals have a lower CO_2 demand. Matching supply and demand is key to ensure the economic viability of the process. Predicting the amount of CO_2 that can be utilized globally is difficult. Several studies have been conducted that give a range between 300 Mt/y in 2016 (Aresta *et al.*, 2013) to 7 Gt/y by 2030 (Global CO2 Initative, 2016). However, the commonly accepted view is a range of 1.5 -2 Gt/yr. for future consumption (IEA (International Energy Agency), 2019). As Europe's share of GDP is about 23% and its share of chemical production is 29%, it has been estimated that around 25% of global CO_2 utilisation could take place in Europe, *i.e.* up to 500 Mt/yr. (Assen *et al.*, 2016).

3.2 CO_2 Emissions

If current trends in greenhouse gas emissions continue, it is predicted that global temperatures will rise by between 3.7°C and 4.8°C above pre-industrial levels by 2100 (Intergovernmental Panel on Climate Change, 2014). There is general agreement with IPCC views that we should be aiming to limit warming to a maximum of 1.5 °C. To reach this objective annual CO_2 emissions need to reduce by 45% from 2010 levels by 2030 and achieve net zero emissions by 2050 ('Intergovernmental Panel on Climate Change', 2013). There are several mechanisms needed to achieve this goal. Scenario modelling by the International Energy Agency gives a number of mitigation options which are combined to reach the necessary targets. These include increasing renewable energy capacity, efficiency measures, expansion of nuclear energy generation and fitting carbon capture and storage units to existing emitters and Bio-CCS. These must be deployed in increasing capacity to curb emissions. Another approach is to dramatically curtail the use of fossil fuels, rapidly switching energy production to low-carbon sources. McGlade and Ekins (2014) state that to give at least a 50 % chance of a lower than 2°C rise, over 80 % of global current coal reserves, 50 % of gas reserves and 33 % of oil reserves must not be used. Either of these approaches to reduce greenhouse gas emissions necessitate a step-chance in technology and policy commitment to achieve them.

There numerous point sources of CO_2 emissions, and targeting appropriate sources for CO_2 utilisation can help to reduce capture costs and influence location choices of CO_2 utilisation technologies. The global energy sector emits the most CO_2 (Figure 4-1). However, the energy industry may not be the most appropriate source of CO_2 when it is to be used as a feedstock for CO_2 utilisation processes due to the large quantity and varying composition of the emissions and relative lower concentration of CO_2 when compared with other sources. Most CO_2 utilisation processes would need only a small percentage of the total CO_2 emitted from the energy provider, which could be taken via a slipstream. However, this is not likely to be the most economically viable route to sourcing CO_2 unless CCS and CCU technologies are integrated (i.e. CCS is deployed to decarbonise the energy provider and some captured CO_2 is diverted for use instead of storage) as other higher purity, lower volume sources are more likely to match the requirements for CCU.

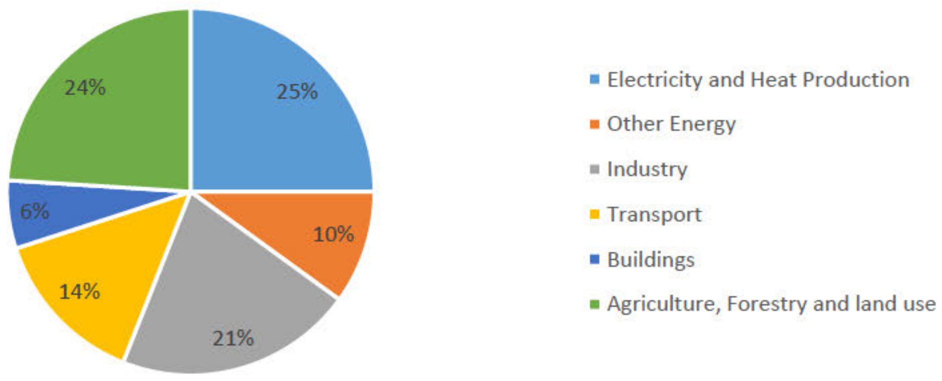

Figure 3.1 Global GHG Emissions by Sector. IPCC 2014 (Stocker et al., 2013)

Other large emission categories are the transport and agriculture, forestry and land use sectors. Many of these emissions originate from non-stationary sources: non-point sources can only be captured using technologies that take CO_2 directly from the air (called Direct Air Capture or DAC) once the CO_2 has entered the atmosphere. Industrial processes accounted for 21% of emissions in 2014. It In order to limit global warming to 1.5°C, industrial emissions will need to decrease by 65-90% by 2050 ('Intergovernmental Panel on Climate Change', 2013). Although many industrial processes strive for emission reductions through efficiency measures, the IPCC has stated that efficiency will not be sufficient to meet required reductions ('Intergovernmental Panel on Climate Change', 2013). Therefore, pathways to reduced emissions via alternative or new technologies are necessary such as electrification and CCUS (carbon capture utilisation and storage). For a number of industries emission reduction technologies such as CCU that also could have an economic benefit or lower economic penalty are being preferentially explored.

Industrial emissions come from a range of different processes. Table 4-1 shows the emissions from industrial sectors in Europe. The European Pollution Release and Transfer Register (E-PRTR) is a compulsory Europe-wide register of pollutants arising from industrial facilities. It contains data reported annually by more than 30,000 facilities within 9 industrial sectors across Europe. A facility must report data annually to the E-PRTR if it exceeds certain thresholds – the threshold for CO_2 is 0.1 Mt/yr.

The three largest emitters of CO_2 are the chemical, construction and metals industries. These industries are identified as harder to decarbonise and the chemicals industry in particular is interested in the use of CO_2 as a carbon feedstock (Royal Society, 2017).

Table 3-1 Sources of CO_2 emission in the EU categorised by sector. Adapted from E-PRTR (E-PRTR, no date)

Sector	CO_2 emissions in Europe in 2014 [M tonnes]
Chemicals	245.1
Construction (including manufacture of cement)	144.1
Food and Agriculture	5.9
Metal (including iron and steel industry)	166.0
Mining	7.1
Paper	77.1
Waste	55.5
Other	13.1

3.3 Overview CO_2 Capture technologies

Carbon dioxide for utilisation processes can be obtained from a range of sources; industrial emitters, power generation, fermentation, anaerobic digesters or from the air. Each source will give CO_2 at differing content, purity and humidity presenting challenges in catalyst design or necessitating costly purification and concentration before use.

There are three main types of carbon capture related to power plant emissions; post-combustion, pre-combustion and oxy-fuel combustion. When looking to capture emissions from industrial sources the CO_2 is separated post-process often using similar technologies to post-combustion (Figure 3-2).

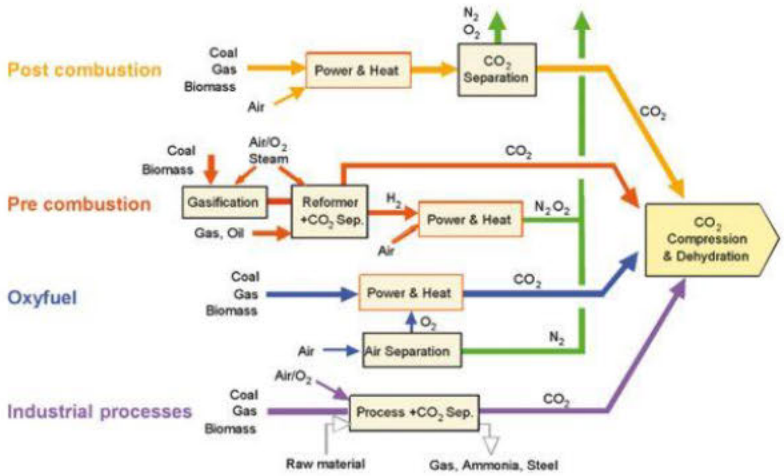

Figure 3.2. CO_2 capture technologies (Moazzem et al., 2012).

For post-combustion capture the current industrial standard uses aqueous solutions of monoethanolamine (MEA) at concentrations of 15-30% (w/w). MEA has problems of toxicity, corrosion, reactive chemistry and evaporative loss and therefore is not an ideal capture agent (Intergovernmental Panel on Climate Change, 2005; Abu-Zahra *et al.*, 2007; Finkenrath, 2011; Moazzem *et al.*, 2012) . It works by a mixture of physi- and chemi-sorption in the strong interaction between CO_2 and basic NH_2 group. The energy requirement for desorption makes the process energy intensive and plant efficiencies are decreased. In an MEA absorber over 70% of its volume is occupied by water which has implication on capital expenditure. Currently, capture technologies are moving towards advanced amine solvents, Figure 3.3 and solid sorbents, particular for post-combustion.

New materials that show selective physisorption are being developed which are more economic, have a smaller energy penalty and are more environmentally friendly (Table 3-2).

Table 3-2 Comparison of average reported energy costs for several post-combustion CO_2 capture processes including maximum and minimum reported values (Reed et al., 2017).

Method	MEA	Advanced Amine	Membrane	Vacuum Swing	High Pressure	Thermodynamic Minimum
Type	TSA	TSA	PSA	VPSA	PSA	--
Av. Capture Cost (MJ/t)	3840	2690	2500	1660	1170	210
Range	2570	1800	1900	1220	860	170
(min/max)	4600	3220	3250	2100	1580	250

TSA = Temperature Swing Adsorption
PSA = Pressure Swing Adsorption
VPSA = Vacuum Pressure Swing Adsorption

New carbon capture technologies such as those shown in Table 3-2 are demonstrating energy cost benefits over traditional amine processes. This is particularly significant for the use of CO_2 as a feedstock for the chemicals industry as having reduced feedstock costs will have an impact on the economic viability of the process. Currently it is observed that the most attractive sources of CO_2 are those that require little or no separation i.e. fermentation or ammonia production. However, if the use of CO_2 as feedstock for the process industry reaches its predicted potential, these sources will not be sufficient and cheap capture and separation technologies will become key to successful implementation.

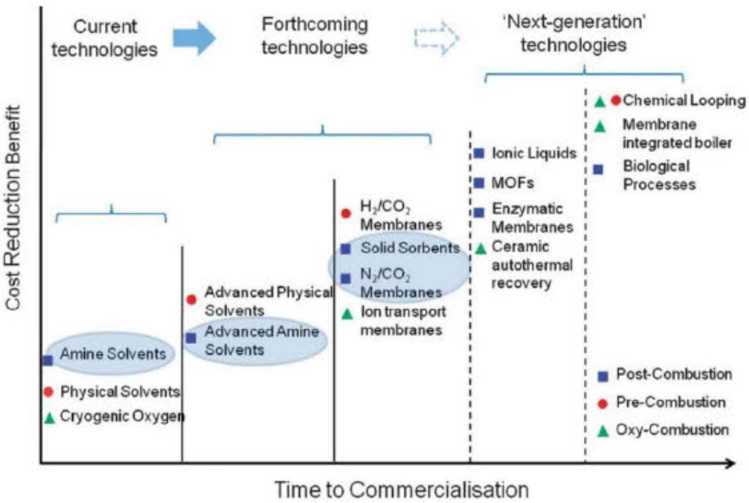

Figure 3.3 Development of new Carbon Capture technologies. (Zhao et al., 2013)

A key target for future CO_2 utilisation processes is sourcing CO_2 from the atmosphere, known as direct air capture (DAC). DAC would provide a closed loop cycle, where CO_2 would be used, then either sequestered in a long term product or re-emitted after a product such as urea or methanol are used. This re-emitted CO_2 could then be captured again providing an essentially closed loop. The significant advantage of DAC is that the capture unit can be sited at any location, and adjacent to the utilisation facility, negating the need for transport of the CO_2 feedstock. However, DAC can be an expensive capture mechanism as the concentration of CO_2 in the atmosphere is approximately 410 ppm (0.041%) and therefore large amounts of air must be processed to achieve the required amount of CO_2, and the sorbent material or process must be highly selective towards CO_2 over other gases. The majority of DAC technologies are currently in low to mid-level technologies readiness with a few reaching small-scale deployment (Koytsoumpa *et al.*, 2018). One notable exception to this is Climeworks[3]. Climeworks have constructed a commercial DAC facility which will capture 900 tonnes of CO_2 annually to be supplied to a greenhouse. However, costs will need to be significantly reduced before widespread deployment.

3.4 Identifying CO_2 Sources in Europe

CO_2 utilisation technologies of considerable interest in Europe both from an emissions reduction and circular economy perspective (VCI *et al.*, 2009; Wilson *et al.*, 2015; Bazzanella *et al.*, 2017; Zimmerman *et al.*, 2017). Hence, Europe is used here as an example of how promising opportunities for CO_2 utilisation can be identified. The use of CO_2 as a feedstock in the circular economy necessitates identifying the amount of CO_2 available, the locations of emitters and the surrounding infrastructure. Emitters to the environment in Europe must publish data on their emissions if they emit more a specified amount per year, this data is gathered in the European Pollutant Release and Transfer Register (E-PRTR)[4]. The E-PRTR is a compulsory Europe-wide register that provides key environmental data regarding pollutants from industrial facilities in European Union Member States and in Iceland, Liechtenstein, Norway, Serbia and Switzerland. The register contains data reported annually by more than 30,000 industrial facilities within 9 industrial sectors, covering 65 economic activities across Europe. A facility must report data annually to the E-PRTR if it exceeds certain set criteria thresholds, set at 0.1Mt/yr. for CO_2. Data is reported by the individual facilities to authorities in their respective countries which is then checked for quality before being reported to the European Commission and European Environmental Agency for compiling into the E-PRTR.

[3] https://climeworks.com/

[4] https://prtr.eea.europa.eu/#/home

Total emissions of CO_2 in Europe from industrial facilities included in the E-PRTR amounted to 1,779 Mt in 2014. The E-PRTR data for CO_2 has been categorised based on industrial sector to identify emission sources (Table 3-3). There are many facilities with emissions below 0.1 Mt per annum, however due to economics of installing carbon capture technologies at these smaller emitters it is unlikely that these would be a key target for the near-term deployment of CCU technologies. The first targets for CCU will most likely be larger emitters looking to decarbonise and avoid emission penalties such as the ETS.

Table 3-3 Sources of CO_2 emission in the EU categorised by sector. Adapted from E-PRTR

Sector	CO_2 emissions in 2014[M tonnes]
Chemicals	245.1
Construction (including manufacture of cement)	144.1
Energy	1,065.5
Food and Agriculture	5.9
Metal (including iron and steel industry)	166.0
Mining	7.1
Paper	77.1
Waste	55.5
Other	13.1

By utilising data from the E-PRTR, mapping can be produced showing the location of emitters to chemical parks and other industry and hence identifying possible symbiotic opportunities. Figure 3-1 shows the location of emitters over 0.1Mt/yr. across Europe and clusters of large emitters in northern Europe. However, although this shows that there are numerous point sources, mapping and identifying the key sources of CO_2 identified above is more beneficial to gain insight to target locations for CCU technologies.

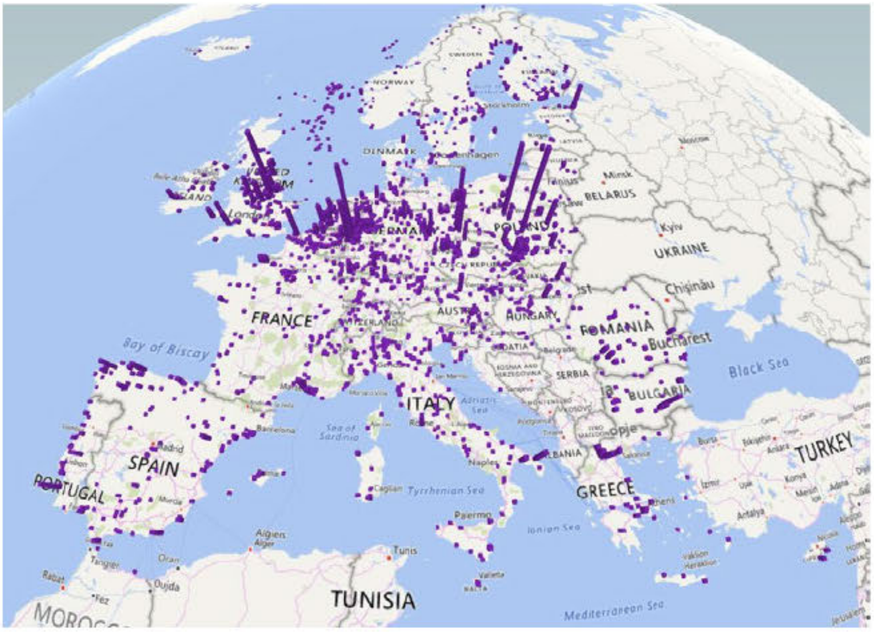

Figure 3.4 Map of location of sources of CO_2 emission in the EU. Adapted from E-PRTR.

The E-PRTR database shows that there is a wide range of CO2 sources across Europe (figure 5) producing more than sufficient CO_2 emissions to meet the demand that could be utilised as a feedstock for the chemical industry. Power generation is the most prevalent emitter of CO_2, this sector comprised 19 the top 20 emitters of CO_2 in the EU (Table 1-3). It should be noted that the data utilised here is from the 2014 E-PRTR and hence, some coal-fired power plants have since closed.

Table 3-4 Top 20 emitters of CO_2 in EU 2014. Adapted from E-PRTR

CO_2 Emission [Mt/yr]	Name of facility	Location	Country	Main Activity
8.96	U.S.Steel s.r.o.	Košice	Slovakia	Manufacture of basic iron and steel and of ferro-alloys
9.19	Longannet Power Station	Kincardine	United Kingdom	Production of electricity
9.21	West Burton Power Station	Retford	United Kingdom	Production of electricity
9.22	E.On Uk Plc, Ratcliffe-On-Soar Power Station	Nottingham	United Kingdom	Production of electricity
9.68	Eesti Energia Narva Elektrijaamad AS, Eesti elektrijaam	Auvere küla, Vaivara vald	Estonia	Production of electricity
10.3	"TETs Maritsa iztok 2" EAD	Kovachevo	Bulgaria	Production of electricity
10.9	Enel Produzione SpA - Centrale di Torrevaldaliga Nord	CIVITAVECCHIA	Italy	Production of electricity
11.4	Elektrownia "KOZIENICE" S.A.	Świerże Górne	Poland	Production of electricity
11.7	Kraftwerk Schwarze Pumpe	Spremberg	Germany	Production of electricity
11.8	PPC S.A. SES AGIOY DHMHTRIOY	AGIOS DIMITRIOS, ELLISPONTOS	Greece	Production of electricity
11.9	Vattenfall Europe Generation AG Kraftwerk Lippendorf	Böhlen	Germany	Production of electricity
12	CENTRALE TERMOELETTRICA Federico II (BR SUD)	BRINDISI	Italy	Production of electricity
18.7	Kraftwerk Boxberg	Boxberg/O.L.	Germany	Production of electricity
18.8	RWE Power AG	Eschweiler	Germany	Production of electricity
23.7	Drax Power Station	Selby	United Kingdom	Production of electricity
24.5	Vattenfall Europe Generation AG Kraftwerk Jänschwalde	Peitz	Germany	Production of electricity
24.9	Elektrownia Pątnów II Sp.z o.o.	Konin	Poland	Production of electricity
27.2	RWE Power AG Kraftwerk Niederaußem	Bergheim	Germany	Production of electricity
32.4	RWE Power AG Kraftwerk Neurath	Grevenbroich	Germany	Production of electricity
36.8	PGE Górnictwo i Energetyka Konwencjonalna S.A., Oddział Elektrownia Bełchatów	Rogowiec	Poland	Production of electricity

3.5 Mapping of Infrastructure

Carbon sources located close to current chemical and process industries are highly desirable as this reduces the costs of transport pipelines and associated infrastructure. The major European chemical parks have been identified as prime locations with existing infrastructure (Table 3-5) which could be utilised for new process industries using non-conventional carbon sources. For this reason, each map of industrial sector carbon sources is plotted alongside the chemical parks to identify synergies.

Table 3-5 Major European chemical parks included in the mapping. Adapted from E-PRTR

Name	City	Country
Chemiepark Linz	Linz	Austria
Schwechat	Schwechat	Austria
INEOS Antwerp site	Antwerp	Belgium
Port Of Antwerp	Antwerp	Belgium
Tessenderloo	Tessenderloo	Belgium
Kohtla-Järve	Kohtla-Järve	Estonia
Kokkola Industrial Park	Kokkola	Finland
Porvoo	Porvoo	Finland
Chemparc, Aquitaine	Pau	France
Fos-Lavera-Berre	Fos sur Mer	France
Port Jérôme	Lillebonne, Notre Dame de Gravenchon	France
Port of Le Havre	Le Have, Port-Jérôme	France
Port of Rouen	Rouen	France
Agro-Chemie Park Piesteritz	Piesteritz	Germany
BASF Schwarzheide GmbH	Schwarzheide	Germany
BASF SE, Ludwigshafen	Ludwigshafen	Germany
Castrop-Rauxel	Castrop-Rauxel	Germany
ChemCoast Park Brunsbüttel	Brunsbüttel	Germany
ChemiePark Bitterfeld Wolfen	Bitterfeld Wolfen	Germany
Chemiepark Knapsack	Huerth	Germany
Chemie- und Industriepark Zeitz	Zeitz	Germany
Chempark Dormagen	Dormagen	Germany
Chempark Krefeld-Uerdingen	Krefeld-Uerdingen	Germany
Chempark Leverkusen Currenta	Leverkusen	Germany
GENDORF Chemical Park	Burgkirchen a.d.Alz	Germany
Industrial Park Dorsten-Marl	Dorsten	Germany
Industriepark Höchst	Frankfurt-Höchst	Germany
IndustriePark Lingen	Lingen	Germany
Industriepark Premnitz	Potsdam	Germany
Industriepark Schwarze Pumpe	Spremberg	Germany
Industriepark Solvay Rheinberg	Rheinberg	Germany
industriepark walsrode	Walsrode	Germany
InfraLeuna GmbH	Leuna	Germany
Krefeld-Uerdingen Currenta	Krefeld-Uerdingen	Germany
Marl Chemical Park	Marl	Germany
NUON Industriepark Oberbruch	Oberbruch	Germany
Schkopau	Schkopau	Germany
Schwedt/Oder PCK Raffinerie GmbH	Schwedt	Germany
Stade	Stade	Germany
Wolfgang Industrial Park	Hanau	Germany
Pétfürdö	Pétfürdö	Hungary
Hellisheiði ON-Power	Hengill	Iceland
Monksland	Monksland	Ireland
Porto Marghera	Porto Marghera	Italy
Środa Śląska	Środa	Poland
Turek	Turek	Poland
ZILS - Sines Industrial and Logistics Zone	Sines	Portugal
Strážske Chemko	Strážske	Slovakia
AEQT - Tarragona Chemical Cluster	Tarragona	Spain
Huelva	Huelva	Spain
Stenungsund	Stenungsund	Sweden
Infrapark Baselland	Muttenz	Switzerland
Solvay Ind.park	Bad Zurzach	Switzerland

Chemelot	Geleen	The Netherlands
Chemical Cluster Delfzijl	Delfzijl	The Netherlands
EMMTEC Industry & Business Park	Emmen	The Netherlands
Port of Amsterdam	Amsterdam	The Netherlands
Port of Rotterdam	Rotterdam	The Netherlands
Valuepark Terneuzen	Terneuzen	The Netherlands
AkzoNobel R&D centre Felling UK	Felling	United Kingdom
Grangemouth	Grangemouth	United Kingdom
Saltend Chemicals Parks	Hull	United Kingdom
Wilton International	Middlesbrough	United Kingdom

3.6 Identifying optimal sources of CO_2 for utilisation

Sources of CO_2 for CO_2 utilisation have been studied by Naims (Naims, 2016) and Von der Assen (Assen *et al.*, 2016). The two works use different methodologies to select the most promising sources. The Naims' assessment was based on economics and the Von der Assen *et al.* study was based on an environmental merit order. Both studies used extensive literature searches to ascertain benchmarked data for best practice scenarios for CO_2 emitters. Naims compared the cost of CO_2 captured and CO_2 avoided to create a merit order, whilst, Von der Assen *et al.* created environmental merit order curves based on environmental impacts as defined by comparative life cycle analysis (LCA) studies. The two assessments do overlap although both do not cover exactly the same CO_2 sources. For example, the Naims study does not analyse retrofit post-combustion onto power generation, only pre-combustion and neither does it consider fermentation processes within Europe.

Both studies conclude that the purest CO_2 sources should be targeted first:

- Hydrogen production
- Gas processing
- Ethylene oxide manufacture
- Ammonia production
- Bio-ethanol fermentation (assessed by Naims only and based on North America and Brazil)

Followed by subsequent targets of lower purity:

- Paper and pulp industry
- Integrated Gasification Combined Cycle (IGCC)
- Iron and Steel
- Cement

These conclusions are unsurprising since the major inhibiting factor in CO_2 capture is the energy required for the capture and separation processes. The energy needed will affect both the cost and environmental implications of the process. Therefore, targeting higher purity streams of CO_2 will keep energy requirements to a minimum as smaller volumes of emitted gas will need to be processed to result in the same volume of purified CO_2 when compared with a more dilute source. Naims concludes that for near-term scenarios, high purity CO_2 which can be captured for low cost of approximately €33/tonne should be sufficient. Von der Assen notes that increases in ethanol plants and biogas fermentation will lead to new relatively pure CO_2 sources which will be environmentally beneficial from a capture perspective. Due to the lower CO_2 concentration in the emissions from the power sector, most of the largest emitters are not included in the primary target sources. The power sector, due to its large emission portfolio, may also be more suited to carbon capture and storage technologies whereby larger volumes of CO_2 could be sequestered than could be dealt with in CO_2 utilisation processes

The utility of this data can be increased by limiting it to only those industries identified as key CO_2 sources for utilisation (Figure 3-1 and Table 3-6). These key sources total emissions of over 350 Mt CO_2/yr. which if utilised would represent a significant reduction in emissions. To enable industrial symbiosis, CO_2 sources located close to current process industries are highly desirable as this reduces the costs of transport pipelines and associated infrastructure. Therefore, Figure 3.5 also shows the proximity of these key emitters to key chemical parks. It can be observed from the mapping that the most prevalent source of CO_2 is the cement industry, as although the steel industry is a greater contributor to emissions there are fewer point sources. However, it is predicted that CO_2 capture from the cement industry will be costlier than other options and therefore, although less numerous, higher purity, and cheaper capture cost sources should be targeted first.

Table 3-6 Key sources of CO_2 in Europe. Adapted from E-PRTR and Naims, 2016.

CO_2 Source	CO_2 concentration [%]	Emission per year [Mt CO_2/year]	Cost [€/t CO_2]	Number of point sources emissions over 0.1 Mt/yr
Hydrogen Production	70-100	5.3	30	15
Natural Gas Production	5-70	5.0	30	10
Ethylene oxide Production	100	17.7	30	6
Ammonia Production	100	22.6	33	27
Paper Pulp Industry	7-20	31.4	58	35
Coal to Power (IGCC)	3-15	3.7	34	3
Iron and steel	17-35	151.3	40	93
Cement	14-33	119.4	68	212
Total		356.4		

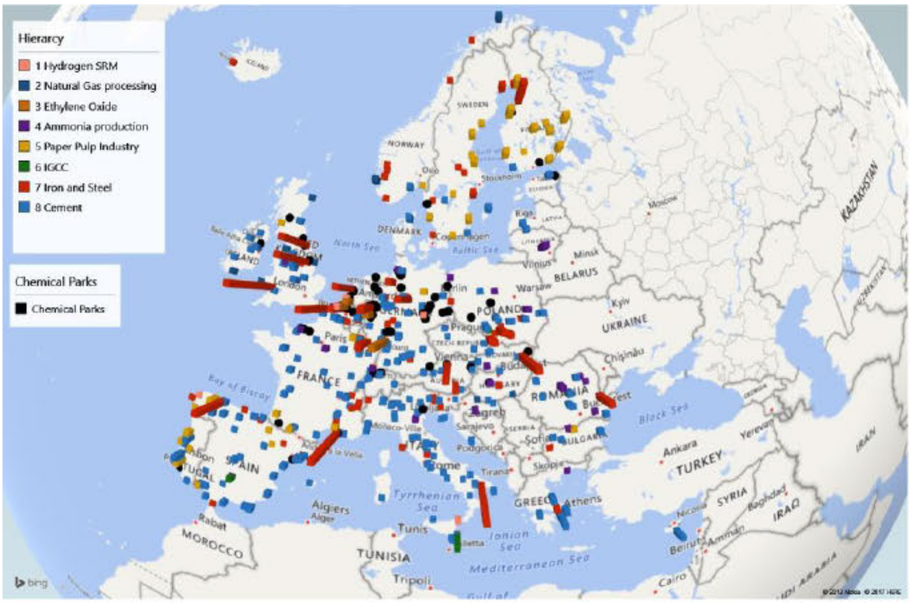

Figure 3.5 Map of key sources of CO_2 in Europe. Adapted from E-PRTR

3.7 Description of the most promising CO_2 sources

3.1.1 Steam Methane Reforming (SMR) to produce Hydrogen

Steam methane reforming is used to produce most of the current hydrogen supply. Methane (CH_4) is reacted with high temperature steam at 700-1000 °C under pressure using a catalyst to promote the reaction $CH_4 + H_2O \rightarrow CO + 3H_2$. Subsequently, the water-gas shift reaction takes place to convert the produced carbon monoxide and remaining water to hydrogen and carbon dioxide. The process results in high purity hydrogen and carbon dioxide streams. SRM facilitates generally emit between 0.1-0.8 Mt of CO_2 per annum. There are 16 SRM facilities listed in the E-PRTR, emitting between 0.136-0.805 Mtonnes of CO2 per annum (Table 3-7 and Figure 3.6).

Table 3-7 Emissions of CO_2 from Steam Reforming of Methane facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
0.136	Linde France Usine de Chalampé	CHALAMPE	France
0.152	AIR LIQUIDE FRANCE INDUSTRIE - BELLE ETOILE	SAINT-FONS	France
0.168	Air Liquide Italia Produzione - Impianto Produzione Idrogeno Melilli	MELILLI	Italy
0.191	AIR LIQUIDE IBERICA DE GASES	ARTEIXO	Spain
0.196	AIR LIQUIDE HYDROGENE SMR Lavéra	MARTIGUES	France
0.246	Linde Gas Produktionsgesellschaft mbH & Co. KG / TOTAL	Spergau	Germany
0.261	AIR LIQUIDE HYDROGENE	NOTRE-DAME-DE-GRAVENCHON	France
0.262	Boc Limited, Seal Sands Boc Hydrogen Plant	Middlesbrough	United Kingdom
0.278	Air Products Nederland BV (Botlek)	Botlek Rotterdam	Netherlands
0.313	Linde Gas Italia Srl - Sito di Milazzo	MILAZZO	Italy
0.343	HYCO (LA POBLA DE MAFUMENT)	Pobla de Mafumet, La	Spain
0.393	Servizi Milazzo Srl	MILAZZO	Italy
0.417	Linde Gas Produktionsgesellschaft mbH & Co. KG	Leuna	Germany
0.477	AIR LIQUIDE LARGE INDUSTRY	Antwerpen	Belgium
0.616	Air Products HyCo 4 (Botlekweg)	Botlek Rotterdam	Netherlands
0.805	Air Liquide Industrie BV	Botlek Rotterdam	Netherlands

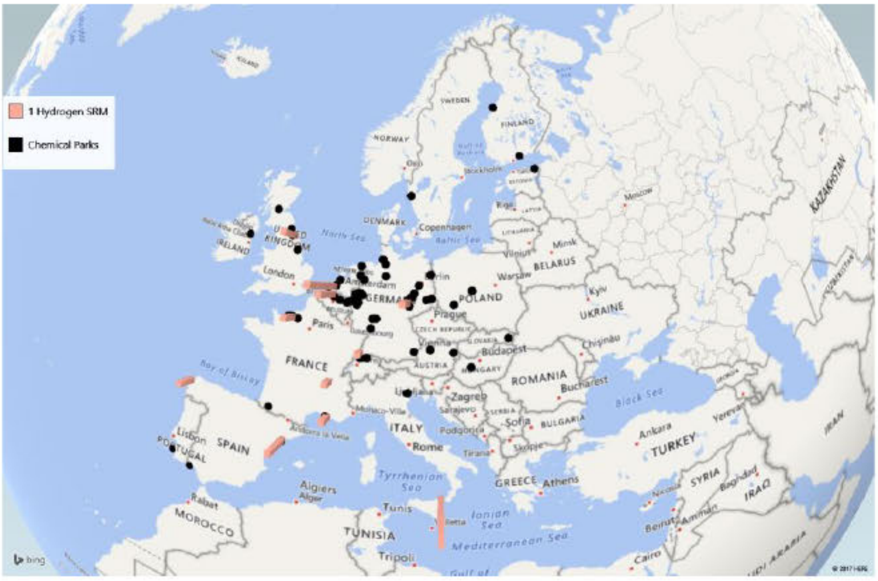

Figure 3.6 Locations of emissions of CO_2 from Steam Reforming of Methane facilities in Europe

3.1.2 Natural Gas Processing

Natural gas does not have the purity needed for further processing when it is extracted. CO_2 and other acid gases such as H_2S must be removed from natural gas before it can be used. Typically, amine adsorption processes are used to remove the CO_2 leading to a high purity CO_2 stream which could be utilised to produce CO_2-derived products. Global emissions of CO_2 from natural gas processing that could be utilised are estimated to be around 50 Mt/year (Intergovernmental Panel on Climate Change, 2005) and typical plant emissions range from 0.1-1Mt/y. There are 10 listed facilities in listed in the E-PRTR (Table 3-8 and Figure 3.7).

Table 3-8 Emissions of CO_2 from Natural Gas Processing facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
0.115	MOL Magyar Olaj- és Gázipari Nyrt.	Algyő	Hungary
0.211	OMV Austria Exploration u. Production	Aderklaa	Austria
0.217	Perenco UK Limited, Dimlington Gas Terminal	Hull	United Kingdom
0.247	South Hook Lng Terminal	Milford Haven	United Kingdom
0.324	Golden Eye Module	Peterhead	United Kingdom
0.427	CPS I, II, III	Virje	Croatia
0.563	Barrow Gas Terminals - North And South	Barrow-In-Furness	United Kingdom
0.652	Bord Gais Energy Ltd	Cork	Ireland
1.04	Hammerfest LNG	Ukjent Kode Benyttet (9601)	Norway
1.19	Gassco Kårstø	Tysværvåg	Norway

Figure 3.7 Locations of emissions of CO_2 from natural gas processing facilities in Europe. Adapted from E-PRTR.

3.1.3 Ethylene Oxide Production

Ethylene oxide is produced by the oxidation of ethylene and requires a silver catalyst to promote the reaction. Ethylene oxide is a used as an intermediate to produce many industrial chemicals including polymers and ethylene glycols. High purity CO_2 is produced in the production of ethylene oxide which must be removed. Six ethylene oxide facilities producing more than 0.1 Mt CO2/yr. are listed in the E-PRTR producing a combined emission of 17.7 Mtonnes/yr. of CO_2 (Table 3-9 and Figure 3.8); although ICIS[5] lists 12 plants in Europe, it is presumed that the other six facilities have emissions of less than 0.1 MT/yr.; however these may be of interest to end users who require smaller volumes of CO_2.

Table 3-9 Emissions of CO_2 from ethylene oxide production facilities in Europe. Adapted from E-PRTR

CO_2 emission MTonnes/yr	Facility Name	City	Country
0.19	INEOS	Zwijndrecht	Belgium
1.92	Shell Nederland Chemie BV (Moerdijk)	Moerdijk	Netherlands
2.76	Dow Benelux BV (Hoek)	Hoek	Netherlands
2.84	INEOS Köln GmbH	Köln	Germany
3.08	BASF ANTWERPEN	Antwerpen	Belgium
6.91	BASF SE	Ludwigshafen am Rhein	Germany

[5] https://www.icis.com/resources/news/2013/04/13/9658385/chemical-profile-europe-ethylene-oxide/

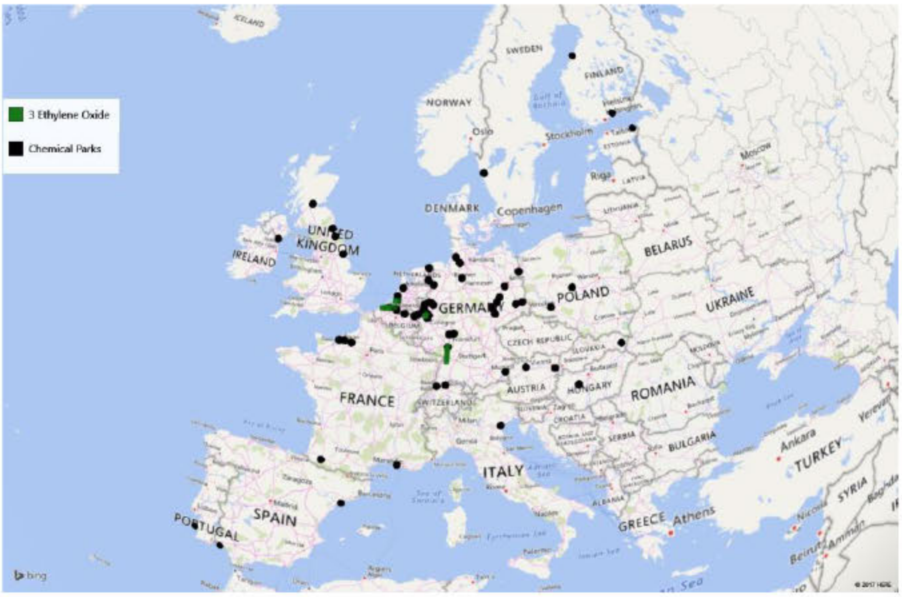

Figure 3.8 Locations of emissions of CO_2 from ethylene oxide production facilities in Europe. Adapted from E-PRTR

3.1.4 Ammonia Production

Ammonia produced via the Haber process is a bulk chemical and predominantly used as a fertilizer, often further processing into urea. Production combines hydrogen (predominately from natural gas, CH_4) with nitrogen to produce ammonia, NH_3. CO_2 is produced during the production of the hydrogen. Ammonia production contributes around 1% of global GHG emissions (Intergovernmental Panel on Climate Change, 2005). The production of urea from ammonia and CO_2 utilises more than 100Mt/CO_2 per year (Aresta *et al.*, 2013), however there are still significant CO_2 emissions that are no utilised. There are 27 facilities producing ammonia with emissions ranging from 0.1-3.2 Mtonnes per year listed in the E-PRTR, the 10 largest emitters are listed in Table 3-10 Table 8, whilst Figure 3.9 shows the location of all 27 facilities.

Table 3-10 Emissions of CO_2 from ammonia production facilities in Europe.

CO_2 emission MTonnes/yr	Facility Name	City	Country
0.807	YARA ITALIA SpA - STAB. FERRARA	FERRARA	Italy
0.862	Duslo a.s.	Šaľa	Slovakia
0.896	Nitrogénművek Zrt.	Pétfürdő	Hungary
0.913	ANWIL S.A.	Włocławek	Poland
0.943	YARA Brunsbüttel GmbH	Büttel	Germany
1.44	Zakłady Chemiczne "POLICE" S.A.	Police	Poland
1.57	SC AZOMURES SA	TARGU MURES	Romania
1.89	Zakłady Azotowe "Puławy" S.A.	Puławy	Poland
2.38	AB "Achema"	Jonalaukis	Lithuania

3.18	YARA Sluiskil BV	Sluiskil	Netherlands

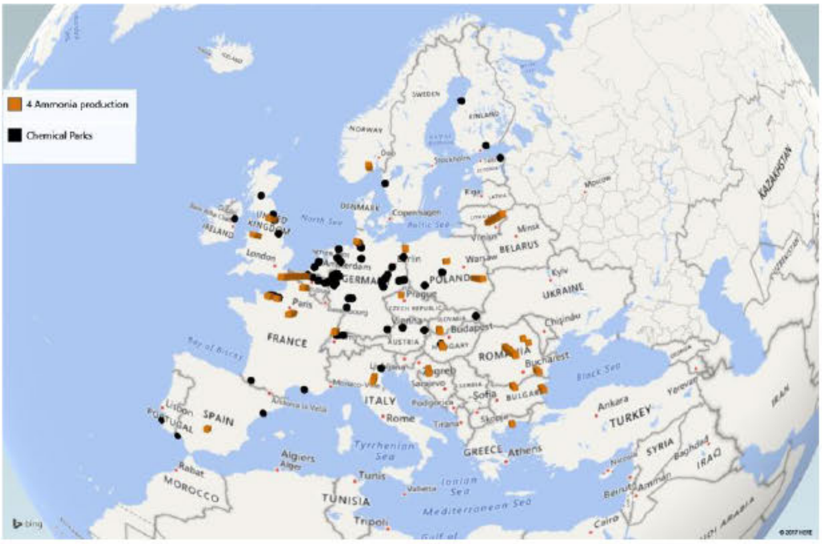

Figure 3.9 Locations of emissions of CO_2 from ammonia production facilities in Europe. Adapted from E-PRTR.

3.1.5 Paper Pulp Industry

The paper pulping industry is highly energy and raw material intensive and has high CO_2 emissions (Moya *et al.*, 2018). A JRC report (Moya *et al.*, 2018) found that CCS would not be a cost effective technology to deploy in the paper industry in Europe, however bio-CCS may be an option. Subsequently the use of the CO_2 to generate income via CCU, may be a future option. The locations of the paper pulp facilities may inhibit the use of the CO_2 in the process sector as they can be in areas close to raw materials (forests) but not to existing infrastructure for chemical plants. Therefore, cost of building the necessary infrastructure or transporting the CO_2 to the required location for use may be prohibitive. There are 35 facilities in Europe with emissions ranging from 0.1 – 2 Mtonnes per year. Facilities are predominantly clustered in Finland, Sweden, Spain and Portugal.

Table 3-11 Emissions of CO_2 from the 10 largest emitting paper pulp production facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
1.26	Complexo Industrial de Setúbal da Portucel	SETÚBAL	Portugal
1.36	CEASA ENCE- FÁBRICA DE NAVIA	NAVIA	Spain
1.37	Metsä Fibre Oy, Joutsenon tehdas	PULP	Finland
1.49	Metsä Fibre Oy Kemin tehdas	KEMI	Finland
1.54	Metsä Fibre Oy, Rauman tehdas	RAUMA	Finland
1.59	STORA ENSO OYJ, ENOCELLIN TEHDAS	UIMAHARJU	Finland
1.59	Skutskärs Bruk	SKUTSKÄR	Sweden
1.83	Södra Cell Mönsterås	MÖNSTERÅS	Sweden
1.89	UPM KYMMENE OYJ, UPM, Pietarsaari	PIETARSAARI	Finland
1.97	Zellstoff Stendal GmbH	Arneburg	Germany

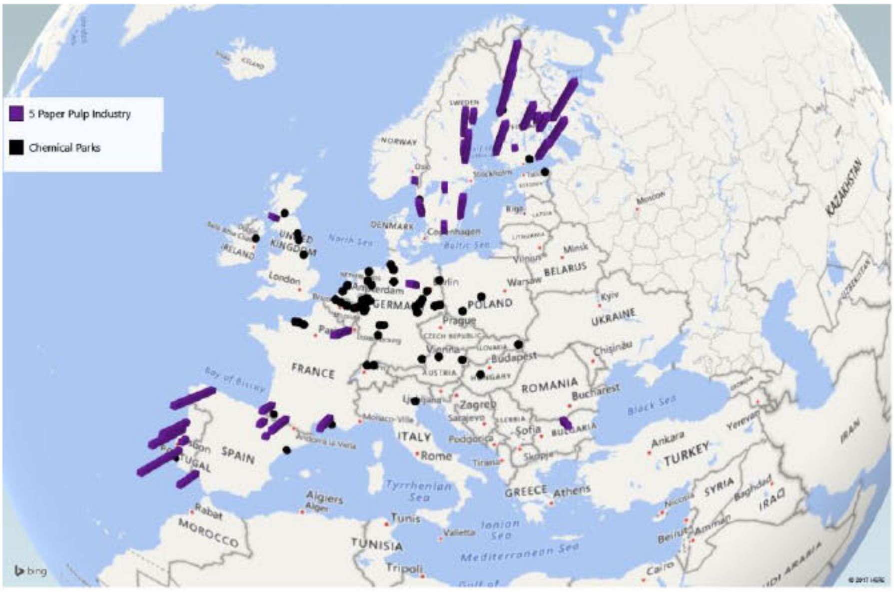

Figure 3.10 Locations of Emissions of CO_2 from paper pulp facilities in Europe

3.1.6 IGCC

Integrated gasification combined cycle (IGCC) power plants use a gasifier to turn a carbon feedstock (usually coal) into synthesis gas (CO and H_2) which is then used in gas and steam turbines to produce electricity. IGCC can be combined with carbon capture technologies as the higher concentrations of CO_2 in the exhaust streams make capture easier than in traditional power plants where the CO_2 is more dilute. Three facilities are listed in Europe (Table 3-12 and Figure 3.11) although there are predictions that the sector could grow. IGCC can be combined with carbon capture technologies as the higher concentrations of CO_2 in the exhaust streams make capture easier than in traditional power plants where the CO_2 is more dilute.

Table 3-12 Emissions of CO_2 from IGCC facilities in Europe. Adapted from E-PRTR

CO_2 emission MTonnes/yr	Facility Name	City	Country
0.281	TAURON Wytwarzanie Spółka Akcyjna -Oddział Elektrownia Blachownia w Kędzierzynie-Koźlu	Kędzierzyn Koźle	Poland
0.821	ELCOGAS S.A. - CENTRAL TÉRMICA GICC	PUERTOLLANO	Spain
2.68	ISAB SUD IMPIANTO IGCC	PRIOLO GARGALLO	Italy

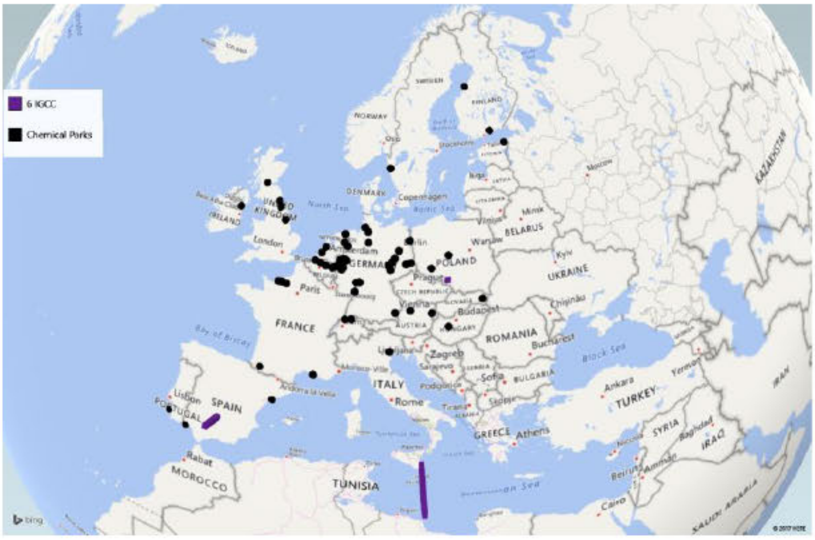

Figure 3.11 Locations of emissions of CO_2 from IGCC facilities in Europe. Adapted from E-PRTR

3.1.7 Iron and Steel production

The production of Iron and Steel is highly energy intensive and hence emission levels are high. Steel production occurs in two stages, firstly iron production then steel making. The iron production process produces the most emissions (70-80% of the total emissions), as iron ore is reduced to metallic iron, usually with coke. The sector is continuously looking to reduce emissions and therefore the utilisation of CO_2 is seen as a promising pathway. Many facilities are located near to chemical parks (Figure 3.12) and hence the required infrastructure and expertise for utilising the CO_2 in the process industry is available.

Table 3-13 Top 10 emitters of CO_2 from iron and steel production facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
5.93	Sahaviriya Steel Industries Uk Limited, Teesside Integrated Iron And Steelworks	Redcar	United Kingdom
5.93	Tata Steel IJmuiden BV	Velsen-Noord	Netherlands
7.17	Scunthorpe Intergrated Iron And Steel Works	Scunthorpe	United Kingdom
7.42	ILVA S.P.A. Stabilimento di Taranto	TARANTO	Italy
7.73	ARCELORMITTAL ATLANTIQUE et LORRAINE SITE DE DUNKERQUE	DUNKERQUE	France
7.92	ArcelorMittal FOS	FOS-SUR-MER	France
8.03	Salzgitter Flachstahl GmbH Werk Salzgitter	Salzgitter	Germany
8.54	Port Talbot Steel Works	Port Talbot	United Kingdom
8.66	voestalpine Stahl GmbH	Linz	Austria
8.96	U.S.Steel s.r.o.	Košice	Slovakia

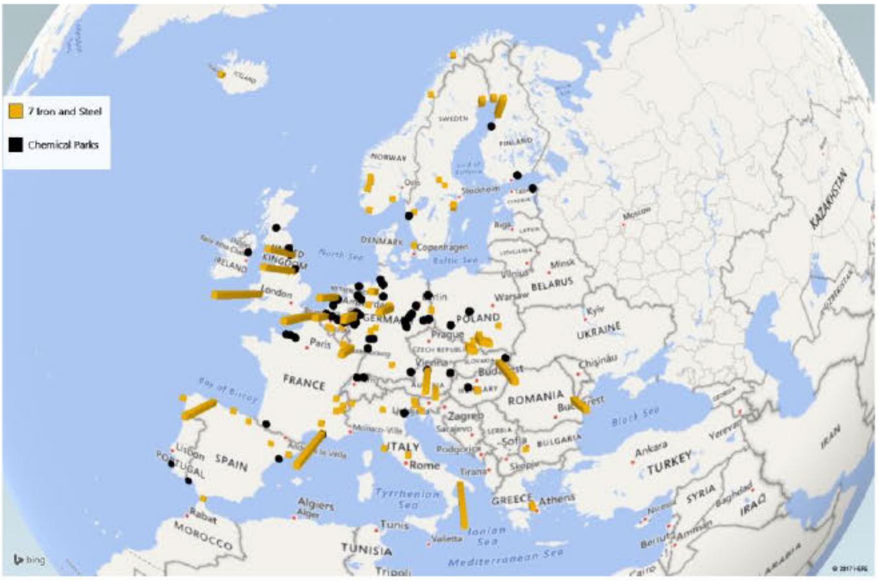

Figure 3.12 Locations of Emissions of CO_2 from iron and steel production facilities in Europe. Adapted from E-PRTR.

3.1.8 Cement industry

Cement production contributes to 5-7% of global GHG emissions with every ton of cement producing around 900kg CO_2 (Benhelal *et al.*, 2013). The production of cement is highly energy intensive and CO_2 emissions occur in predominantly in two areas of the cement making process. Emissions arise from limestone (calcium carbonate) being calcined to produce calcium oxide and the kilns require heating necessitating the burning of fossil fuels. The cement industry is deploying efficiency measures to reduce emissions, but will need carbon capture and utilisation/storage to decarbonised completely. The cement industry has the most entries in the E-PRTR with over 200 facilities emitting more than 0.1 Mt CO2 per year (Figure 3.13). Emissions range from 0.1-2.2 Mt CO2/yr., with the top 10 emitters identified in Table 3-14.

Table 3-14 Ten largest emitters of CO_2 from cement production facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
1.36	CCB sa - Site de Gaurain-Ramecroix	GAURAIN-RAMECROIX	Belgium
1.46	CEMEX Zement GmbH	Rüdersdorf bei Berlin	Germany
1.5	Cementownia Warta S.A.	Trębaczew	Poland
1.51	Centro de Produção de Alhandra	VILA FRANCA DE XIRA	Portugal
1.53	VASSILIKO CEMENT WORKS PUBLIC COMPANY LTD, Vassilikos Plant	ZYGI	Cyprus
1.7	Cementa AB, Slitefabriken	Slite	Sweden
1.72	AALBORG PORTLAND A/S	Aalborg Øst	Denmark
1.73	TITAN CEMENT S.A. - KAMARI PLANT	KAMARI, DERVENOCHORIA	Greece
1.84	Grupa Ożarów S.A.	Karsy	Poland
2.2	Górażdże Cement S.A., Cementownia Górażdże	Chorula	Poland

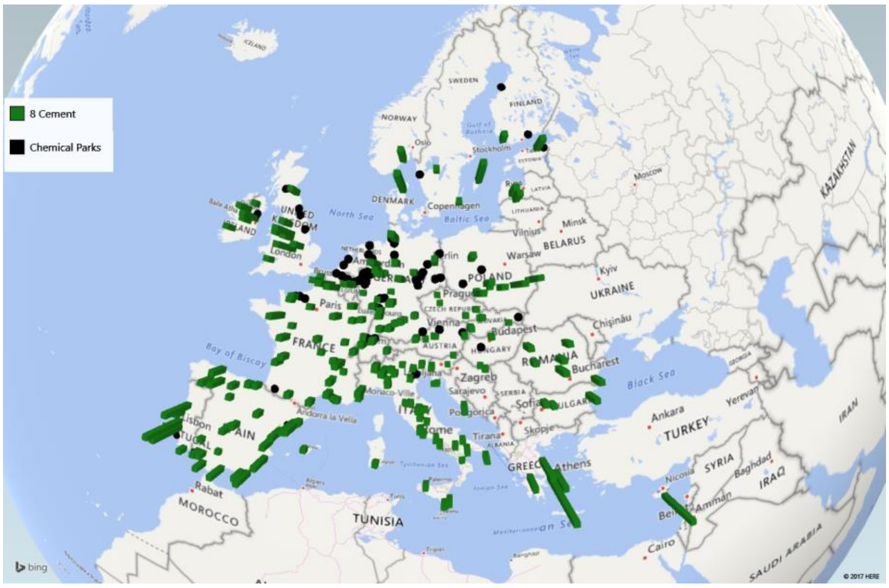

Figure 3.13 Locations of emissions of CO_2 from cement production facilities in Europe. Adapted from E-PRTR.

3.8 Outlook for sources

It is expected that the main change in CO_2 availability will arise from reductions in emissions arising from coal power generation, which is expected to decrease significantly by 2100. Over the medium term, "clean coal" technologies such as integrated gasification combined cycle or pressurized fluidized bed will improve combustion efficiencies and in the longer-term there is expected to be a move away from coal altogether. The relatively ambitious IEA 2 °C scenario of the ETP2015 model foresees a reduction of coal as fuel input for electricity and heat generation from 33.8 EJ (1 EJ = 10^{18} J) in 2012 to 5.1 EJ in 2050, corresponding to a 85% reduction (IEA, 2015). With around 46 % of the global emissions arising from fossil fuel combustion currently coming from coal (Jos G.J. Olivier, Greet Janssens-Maenhout, 2016), reductions in coal use will impact CO_2 availability. However, the impact upon CO_2 utilisation may be limited, as CO_2 from this source is generally of low concentration at 12-14% (Intergovernmental Panel on Climate Change, 2005) and can be contaminated with sulphur and heavy metals such as mercury, making capture and purification (clean-up) more expensive. Consequently, it is expected that CO_2 arising from purer sources will be preferentially utilised as described previously. As a result of the 2018 6^{th} Report from IPCC ('Intergovernmental Panel on Climate Change', 2013), the revised target of less than 1.5 °C temperature rise will require even more effort in terms of emissions reduction.

The report of the Energy Technology Transitions for Industry: Strategies for the next industrial revolution, published by the IEA in 2009 (IEA, 2009), looks at five industrial sectors: iron & steel, cement, chemicals & petrochemicals, pulp & paper and aluminium. It concludes that in order to reach a global emissions reduction of 50% by 2050, industry would need to reduce emissions by

21%, which assumes a near complete decarbonisation of the power sector. However, due to strong growth in demand, such reductions are not expected to be achieved by efficiencies and technology improvements alone. It is projected to be achieved only by including CO_2 capture within the adopted strategies, giving rise to possible opportunities for use of the CO_2 as a feedstock.

Technology changes will determine future industrial emissions and some industrial sectors will be able to reduce emissions more significantly than others. Around 96% of global H_2 production is currently from steam reforming of methane, oil-based or coal gasification (IEA (International Energy Agency), 2012) which result in CO_2 emissions which will only increase if projected increases in H_2 usage transpire. However, a switch to electrolysis of water using renewable energy will mean that CO_2 availability from this source will decrease significantly. Other low-carbon technologies, such as photocatalytic water-splitting or bio-hydrogen/fermentative production are further from commercial reality. Currently H_2 usage is split roughly 50:50 between hydro-treating/hydro-cracking by refineries and ammonia/nitrogen-based fertilizer production by the chemical industries.

One major CO_2 source, natural gas processing, is expected to increase in the medium-term as power generation shifts away from coal and natural gas is used to balance intermittent renewable generation. Projections suggest that natural gas use will increase by 85% between 2007 and 2050 (International Energy Agency, 2010), so CO_2 emissions arising from processing/cleaning the gas prior to its eventual combustion will rise.

3.9 Environmental credentials of carbon

One aspect of CO_2 utilisation that is much discussed is the environmental credentials of the carbon in recycled CO_2 that is used for CO_2 utilisation. It has been argued that any product using captured CO_2 from a process that uses fossil-based fuels is perpetuating fossil-based CO_2 use and a distraction from mitigation (Mac Dowell *et al.*, 2017). This is an interesting argument where one needs to consider the fate of the CO_2. If we burn natural gas and follow the carbon atom, one molecule of methane becomes one molecule of CO_2. Both molecules contain the same carbon atom which was derived from a fossil resource. We could capture that CO_2 molecule and convert it into methane (synthetic methane) again through hydrogenation, Figure 3.14. So, is the new methane molecule derived from fossil carbon? Indirectly yes, it is, however some emissions may be avoided by its re-use. Now let us consider what happens if the CO_2 molecule is released to the atmosphere. It could persist or it could react in a photosynthetic process to produce carbohydrates and oxygen. The carbohydrates produced by the plant contains the same carbon atom that was emitted from the combustion of fossil methane. Using the analogy of the synthetic methane, the carbohydrate produced or biomass, should also be considered to be derived from a fossil-resource, Figure 3.15.

However, generally it is not and the resulting energy would be considered a bio-derived and hence 'green'.

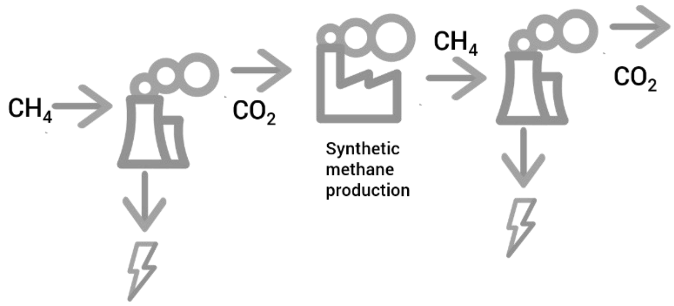

Figure 3.14 Following the carbon atom in producing synthetic methane from fossil methane

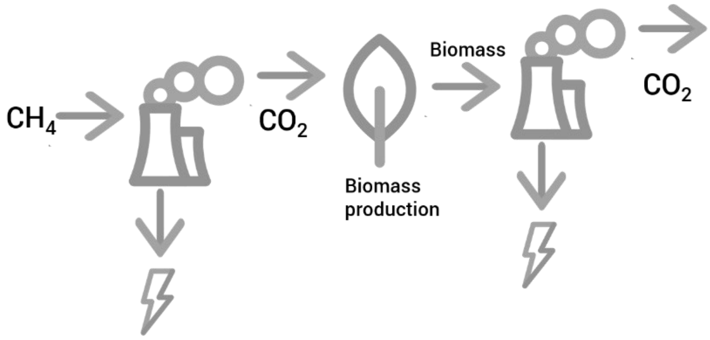

Figure 3.15 Following the carbon atom in producing biomass from fossil methane

Both the synthetic methane and the biomass contain carbon that was initially present in a fossil resource. However, both are now second-life products. When these are consumed by combustion, the carbon is again released as CO_2. Should this be considered to be fossil-carbon? Fossil oil and gas was initially plant and animal life that over millions of years reacted to become hydrocarbons. There is always an interchange between the biosphere and the "hydrocarbonsphere". The difference is that while natural fossilisation occurred quite literally over geological timescales, the chemical and catalytic reduction of CO_2 to hydrocarbons takes place over minutes or hours. Science is being used to accelerate the carbon cycle. However, although this idea seems simple, ensuring that CO_2 utilisation does not contribute to increasing atmospheric CO_2 is vital and hence thorough life cycle analysis (LCA) is needed (von der Assen *et al.*, 2013). Additionally, accounting mechanisms need to ensure that optimal choices are being made and biomass CO_2 or direct air capture (DAC) is not prioritised over using available, unavoidable point source emissions.

Although numerous CO_2 sources exist, CO_2 utilisation should not be employed as an excuse to avoid reducing process emissions. Technology/process improvements, the use of renewable low carbon energy and new production processes which reduce emissions should all be used in preference to deploying CO_2 utilisation technologies. Many CO_2 utilisation technologies do not sequester CO_2 as the products will re-emit the CO_2 upon use, unlike CCS (Bruhn *et al.*, 2016). At best these provide avoided carbon benefits as the carbon molecule is utilised twice when an initial fossil point source emission is used. Only with the inclusion of DAC technologies could a circular synthetic CO_2 cycle be implemented. Therefore, although numerous point sources have been identified here, priority should be given firstly to reducing emissions then utilising CO_2 from the sources hardest to decarbonise.

3.10 Key challenges for CO_2 utilisation

There are a number of key challenges regarding the use of CO_2 as a feedstock for the process industry. The largest is creating economically viable processes that simultaneously have a positive environmental impact when compared to traditional production methods. Theoretically, CO_2 can be used as a carbon source in many process, however whether the theory can be industrially deployed is complex. Comprehensive techno-economic analysis (TEA) is required combined with robust life-cycle analysis (LCA) to ensure process viability. A key cost is the capture of the CO_2. As described above there are plentiful sources of CO_2 but the capture of CO_2 from these sources may not be economically viable using currently available technologies. Other key challenges include:

- Matching volumes of CO_2 from emitters to technology solutions
- Reducing transportation distance
- Decreasing costs of air-capture so CO_2 utilisation technology locations can be decoupled from CO_2 sources
- Decreasing the energy penalty of capture technologies
- CO_2 storage for utilisation
- Standardisation of Life Cycle Analysis to allow comparison between technologies for environmental impacts and CO_2 reduction
- Integration with mechanisms such as EU ETS and carbon taxes
- If CCS deployment to the power industry takes place, putting mechanisms in place to utilise a proportion of the captured CO_2
- Emitters with no significant process industry in close proximity, should CO_2 be transported or new industry be encouraged to locate close to the emitter?
- The need to decarbonise carbon intensive industry may provide a push for deployment of CO_2 utilisation technologies

3.11 Conclusions: Future outlook and potential impact

There are plentiful sources of CO_2 which could be used as a carbon feedstock. Primary targets for sourcing CO_2 should focus on those sources with the highest concentration of CO_2 (hydrogen production, natural gas processing, ethylene oxide manufacture and ammonia production) as the higher concentration of CO_2 reduces the cost of capture. However, larger volumes of CO_2 are available from the iron and steel industry and cement industries, albeit at lower CO_2 concentration. As industries look to decarbonise (particularly the hard to decarbonise iron and steel and cement sectors) there is an observed market pull to deploy CO_2 utilisation technologies to provide an economically beneficial method of reducing CO_2 emissions. As next-generation carbon capture technologies reach the market, other sources of CO_2 may become increasingly economically viable. However, economics, locations close to CO_2 utilisation sites and industrial symbiosis opportunities will be likely to remain the key drivers in choice of CO_2 source.

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4 Emerging industrial Applications of CCU

This chapter comprises of a reprint of a book chapter published by the author in the volume Carbon Dioxide Utilisation: Closing the Carbon Cycle (Styring *et al.*, 2014). The chapter is the sole work of Katy Armstrong.

This chapter explores industrial applications of CO_2 utilisation examining some of the first technologies to emerge from laboratory research into industrial deployment. Written in 2014, few technologies at this point had made the transition through technology readiness levels (TRLs) to deployment. The chapter highlights these technologies and contrasts their deployment stories. Few technologies in 2014 had reached any meaningful large scale deployment and CO_2 utilisation was considered an emerging technology area with considerable scepticism around financial viability or markets. Therefore, deployment was observed predominantly in locations with significant government investment or favourable geographical benefits i.e. access to geothermal energy in Iceland. Conclusions that further investment will be needed to drive future deployment have in hindsight been proven. Significant funding schemes in Europe and prizes such as the Carbon X Prize have catalysed technology deployment and a broader range of CO_2 utilisation companies are now at industrial deployment.

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Styring, Peter, Quadrelli, Elsje Alessandra and Armstrong, Katy (2014) *Carbon Dioxide Utilisation: Closing the Carbon Cycle: First Edition*. First Edit. Edited by P. Styring, E.A. Quadrelli, and K. Armstrong. Elsevier Inc. doi: 10.1016/C2012-0-02814-1.

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5 Assessing the potential of utilization and storage strategies for post-combustion CO_2 emissions reduction

This chapter comprises of a reprint of a research paper by Armstrong and Styring., (2015) . There is a joint 50:50 contribution to the paper between the authors for conceptualization, methodology, formal analysis, investigation, data curation, visualisation, and writing

This chapter explores the emissions reduction potential of three carbon dioxide handling strategies for post- combustion capture; carbon capture and sequestration/storage (CCS), enhanced hydrocarbon recovery (EHR), and carbon dioxide utilization (CDU) to pro-duce synthetic oil. Results show that while CCS can make an impact on CO_2 emissions, CDU will have a comparable effect whilst generating income while EHR will ultimately increase net emissions. The global capacity for CDU is also compared against CCS using data based on current and planned CCS projects. Analysis shows that current CDU represent a greater volume of capture than CCS processes and that this gap is likely to remain well beyond 2020 which is the limit of the CCS projects in the database.

Armstrong, K. and Styring, P. (2015) 'Assessing the Potential of Utilization and Storage Strategies for Post-Combustion CO2 Emissions Reduction', *Frontiers in Energy Research*, 3(March). doi: 10.3389/fenrg.2015.00008.

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Assessing the potential of utilization and storage strategies for post-combustion CO_2 emissions reduction

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The emissions reduction potential of three carbon dioxide handling strategies for post-combustion capture is considered. These are carbon capture and sequestration/storage (CCS), enhanced hydrocarbon recovery (EHR), and carbon dioxide utilization (CDU) to produce synthetic oil. This is performed using common and comparable boundary conditions including net CO_2 sequestered based on equivalent boundary conditions. This is achieved using a "cradle to grave approach" where the final destination and fate of any product is considered. The input boundary is pure CO_2 that has been produced using a post-combustion capture process as this is common between all processes. The output boundary is the emissions resulting from any product produced with the assumption that the majority of the oil will go to combustion processes. We also consider the "cradle to gate" approach where the ultimate fate of the oil is not considered as this is a boundary condition often applied to EHR processes. Results show that while CCS can make an impact on CO_2 emissions, CDU will have a comparable effect whilst generating income while EHR will ultimately increase net emissions. The global capacity for CDU is also compared against CCS using data based on current and planned CCS projects. Analysis shows that current CDU represent a greater volume of capture than CCS processes and that this gap is likely to remain well beyond 2020 which is the limit of the CCS projects in the database.

Keywords: CDU, CCU, enhanced oil recovery, CCS, LCA, CO_2 reduction potential

INTRODUCTION

Society is realizing that we have reached a critical point in our approach to energy use and resulting emissions. There exists an "energy trilemma" where we must consider the security of the energy supply, the costs of that energy, and the environmental impacts created (World Energy Council, 2013). The carbon dioxide utilization (CDU) for chemical synthesis is a growing area of research. Carbon dioxide (CO_2) can be used as a valuable feedstock for chemical production and chemical energy storage (Styring et al., 2014). This impacts on two of the key challenges in the trilemma: the sustainable supply of chemicals and meeting energy demand whilst also reducing CO_2 emitted to the atmosphere. In treating CO_2 as a commodity chemical rather than a waste, it becomes a valuable asset rather than an economic drain. Fossil oils are the primary feedstock for many industrial chemicals, but these are not sustainable as while there is a plentiful reserve of fossil oil and gas, this will ultimately lead to new CO_2 emissions when the chemical is used (Berners-Lee and Clark, 2013; McGlade and Ekins, 2015). If emitted CO_2 is used as an alternative carbon source for the production of these products, net emissions will be reduced and a sustainable pathway for production will be created. CO_2 utilization technologies can either give products that sequester the CO_2 for a lengthy period of time (such as polymers or mineralization) or only for a matter of weeks or days as in the case of hydrocarbon fuels and methanol. However, in the case of fuels, we must also consider longer term storage as is the case with seasonal storage: using renewable power to produce liquid and gaseous fuels that can be stockpiled until they are needed.

It is a misconception that manufacturing fuels and other short lifetime chemicals by CDU will not lead to a reduction in CO_2. These products would traditionally be sourced from fossil oils and once combusted or used would release CO_2 to the atmosphere. It is acknowledged that there are substantial reserves of fossil hydrocarbons, however these are so great that ultimately we will not have the capacity to deal with the emissions from them while trying to achieve the two degree scenario for climate change mitigation (IPCC, 2007). When manufacturing chemicals from CO_2, previously emitted CO_2 will be re-used before it is re-emitted, resulting in a net reduction in emitted CO_2. This is of course a consequence of carbon avoided. While this does not sequester as much CO_2 as if it was stored geologically or is used to produce long life-time products such as a polymer or mineral; but it does provide a sustainable low carbon pathway for the chemicals industry and a net reduction in emissions. This net reduction and the amount of CO_2 that can be utilized to create it should not be disregarded. The chemicals industry needs to become more sustainable and embrace a circular economy and the use of CO_2 as a feedstock enables this (Centi et al., 2013).

CO_2 is a greenhouse gas (GHG) created as an anthropogenic waste product by power generation and many industrial processes. Energy-related emissions of CO_2 in 2013 were 36 Gt (Carbon Dioxide Information Analysis Centre, 2014), and predicted to rise to 43 Gt by 2030 (IEA Energy Technology Perspectives, 2014). The

Doha amendment to the Kyoto Protocol (2012) gives a commitment to aim to reduce GHG emissions by at least 18% below 1990 levels between 2013 and 2020. In the UK, the 2008 Climate Change Act set a legally binding target to reduce the UK's CO_2 equivalent emissions amount by at least 80% from the 1990 baseline by 2050.

Different strategies to reduce CO_2 emissions must be employed to reach these targets (**Figure 1**). The IEA has calculated that in order to give a 50% chance of restricting global warming to 2°C, CO_2 emissions must be reduced by 17 Gt in 2030 and 39 Gt in 2050 against projected emissions. To achieve this, the IEA has modeled CO_2 reductions scenarios, which include carbon capture and storage (CCS), renewables, end-use fuel and electricity efficiency, end-use fuel switching, nuclear power and power generation efficiency, and fuel switching, to give the desired outcome of a less than +2°C rise. Of these technologies, CDU is most often compared with CCS due to the similarities in the capture of CO_2, although how the captured CO_2 is dealt with is often very different.

In CCS, CO_2 is captured from emitters, separated from the other emitted gases, then compressed and transported, usually *via* a pipeline, to a geological storage site. These are often a depleted natural gas/oil wells or a saline aquifers. CCS is an effective method of reducing CO_2 emissions to the atmosphere, but is costly with an estimated 30% parasitic energy loss for a power generator, as well as substantial capital (CAPEX) and operational (OPEX) costs.

There has been considerable debate as to the relative impacts of different carbon capture technologies. It has been a long held belief that CCS represents the best option for carbon dioxide mitigation while giving the cheapest approach to carbon-neutral fuels, still using existing fossil fuel reserves. Furthermore, it is assumed that CO_2 use through enhanced hydrocarbon recovery (EHR) in the form of oil or natural gas will aid the economics of the capture process. It has also been suggested that carbon dioxide capture and utilization (CCU or CDU) will only play a minor role due to the huge volumes of CO_2 that need to be sequestered. In order to address these issues, we have undertaken a number of studies to assess the techno-economic and environmental viability of each of the processes. This has included considering "cradle to gate" and "cradle to grave" scenarios for different technologies in terms of material balances across the processes. Each of the three processes is considered with a common feedstock: captured and purified carbon dioxide that is piped to the point of storage or utilization.

CARBON CAPTURE AND STORAGE

The global status of CCS projects has been compiled by the Global CCS Institute database (2014) "Status of CCS database." The database divides current and proposed CCS plants according to their phase of development: Operate; Execute; Define; Evaluate; Identify. The nature of the capture process is identified, as is the ultimate destination of the CO_2. There are 55 CCS projects currently listed on the database, with a potential capacity of storing approximately 102 Mt CO_2/year by 2020 as shown in **Table 1**.

Of these projects, 13 are in the Operate phase with the majority being located in North America. Of this group of projects, only one is associated with the power generation sector: the Sask Power facility at Boundary Dam in Canada which came online in 2014. The facility has a 1 Mt/year capture capacity and the CO_2 will be transported by a 66-km pipeline to an enhanced oil recovery (EOR) facility. The Boundary Dam project represents the highest single unit capture facility globally, although there are plans for the Gorgon Carbon Dioxide Injection Project in Western Australia to come online in 2016 with the world's largest capture capacity of 3–4 Mt/year. Only two facilities in the Operate phase are in mainland Europe, the Sleipner and Snøhvit projects in Norway that take CO_2 from natural gas processing plants and store the gas in dedicated geological storage facilities. Taking the operational plants only, the current total global capacity is 26.6 Mt/year. If we now include

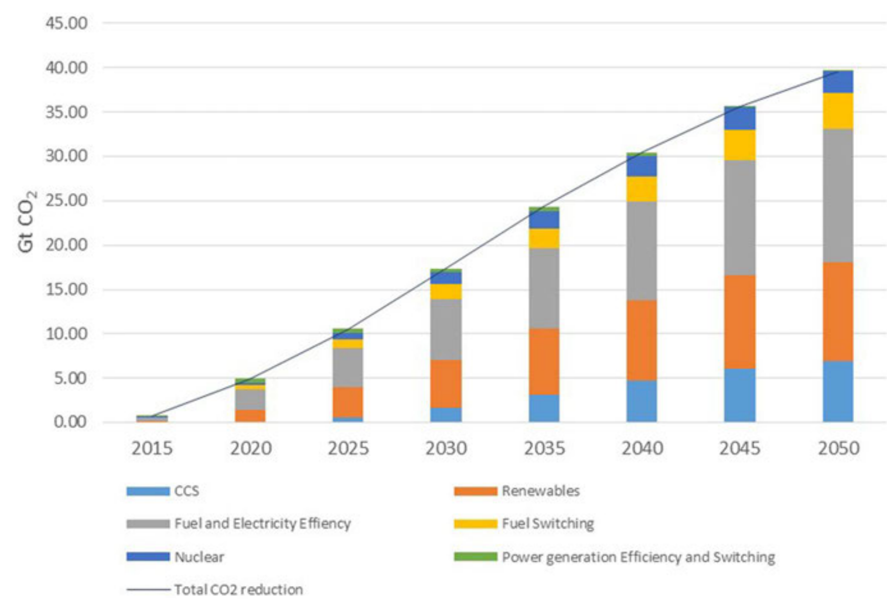

FIGURE 1 | World CO_2 reduction targets to meet the 2°C scenario (2DS) adapted from IEA Energy Technology Perspectives (2014).

Table 1 | The global status of CSS projects in 2014 [adapted from Global CCS Institute database (2014)].

Type of plant	No. of projects	Type of capture	Storage method	Total CO_2 Mt/year	
Chemical production	5	Two industrial separation	3 EOR	4.96	8–9
		Three pre-combustion	2 Geological	3–4	
Coal to liquids	3	Pre-combustion	1 EOR	2.5	5.5
			1 Geological	1	
			1 Unspecified	2	
Fertilizer	4	Industrial separation	3 EOR	2–2.6	4.5–5.1
			1 Geological	2.5	
H_2 production	2	Industrial separation	1 EOR	1	2
			1 Geological	1	
Iron and steel	1	Industrial separation	EOR	0.8	
Natural gas processing	13	Pre-combustion	8 EOR	22.4	29.6–30.1
			5 Geological storage	7.2–7.7	
Oil refining	1	Pre-combustion	EOR	1.2	
Power generation	23	9 Post-combustion	10 EOR	17.7	41.2
		10 Pre-combustion	11 Geological	19	
		4 Oxy	2 Unknown	4.5	
Synthetic natural gas	2	2 Pre-combustion	2 EOR	8.5	
Unknown	1	Unknown	Geological	1	
Total	55			102.3	

those projects in the Execute phase, then the total capacity rises to 34.7 Mt/year as there are an additional nine projects assigned to this phase. None of these are in mainland Europe. Extending this to include projects in the Define phase, there are 14 projects identified which includes 4 projects in the UK and 1 in the Netherlands. However, it is noted that three of these are currently on hold and only the Peterhead and White Rose projects in the UK are in the Front End Engineering Design (FEED) stage. If we still include the mothballed projects, the total global emissions capture total a maximum of 58.5 Mt/year. Of the 36 projects in this latter total, only 12 are dedicated geological storage project (although one may adapt into an EOR project) and 24 are EOR projects. Of the 13 projects currently in operation, 10 are EOR installations. By contrast, the Carbon Recycling International CO_2 to methanol plant in Iceland currently produces 4 Mt/year consuming 5.5 Mt/year CO_2. This is larger than any current or proposed single CCS facility. The energy for the conversion comes from a geothermal source and avoids fossil fuels. This emphasizes the importance of renewable energy in any CDU process. Likewise, it emphasizes the importance of CDU in seasonal energy storage through the production of synthetic gas or liquid fuels.

The database is extensive and describes each process, including capacity, operational phase, and origin of the CO_2 and its destination in storage or HER facilities. It provides an up to date analysis of all project that could come online by 2020. The spreadsheet is too detailed to discuss in this paper and readers are advised to consult it directly. It is available free of charge from the GCCSI reference given above.

CARBON DIOXIDE ENHANCED OIL/HYDROCARBON RECOVERY (CO_2-EOR/EHR)

Carbon dioxide can also be used in EOR or more generally, to include natural gas, EHR. This is similar in many ways to CCS as captured and compressed CO_2 is injected into geological formations. However, these contain trapped hydrocarbons which can be displaced by the injected CO_2. In a perfect case of immiscible EOR, the hydrocarbon and CO_2 are completely immiscible so do not mix. Instead, an equal volume of hydrocarbon is forced out of the well to be replaced by the CO_2. Therefore, the CO_2 is sequestered in the geological structure. By contrast, miscible EOR involves the mixing of the CO_2 and hydrocarbon. Some of the CO_2 is released together with the hydrocarbon while a proportion is sequestered. The relative proportions are dictated by the degree of mixing achieved. In fact, the CO_2 released will be recaptured and re-injected into the formation, however to account for this in the functional unit, it must be considered as being non-sequestered in the single pass first injection. Any gas re-injected would necessarily reduce subsequent functional units of CO_2, so would perturb calculations. In EHR, the product is a hydrocarbon; typically crude oil or natural gas. Therefore, unlike CCS, EHR will produce a product that on refining will represent commercial value. Hydrocarbons that are otherwise uneconomic to extract are therefore suitable for EHR technologies and this is the general driving force.

CARBON DIOXIDE UTILIZATION

In CDU, CO_2 is used as a carbon source to produce new, marketable products. It is in essence CO_2 reuse. CDU technologies can either give products that sequester the CO_2 for a lengthy period of time (such as polymers or mineralization); or only for a matter of weeks or days but also perhaps between seasons, as in the case of fuels and methanol. There are many methods for CDU available which include catalytic reduction and direct addition. A full discussion of these methods is beyond the scope of this paper, so readers are recommended to refer to reviews and textbooks that cover the field in depth [for example Aresta et al. (2013) and Styring et al. (2014)]. However, as many of these chemicals would traditionally be sourced from petrochemicals, manufacturing them from CO_2 will result in a net reduction in emitted CO_2 as shown schematically in **Figure 2**. We should also note that there is a growing interest in harnessing biological processes in CDU, often coupled to the use of renewable energy integration. These include the cultivation of algae and micro-algae in photo-reactors or open raceways (Jansen et al., 2011). This raises issues of sustainability, characterized by the energy-water-food nexus, primarily through the use of agricultural land for energy-related processes. Consequently, there are concerns whether such processes would be economically viable at scale (Aresta et al., 2013), especially given the concurrent needs for food, energy, and chemicals. The concept of the bio-refinery and advanced bio-manufacturing may go some way to addressing this, together with genetic modification of associated organisms, although this has its own controversies. While this paper does not address bioprocesses, it is acknowledged that once algae are harnessed for enhanced aquatic biomass production, there is the potential for large impact. Aresta et al. (2005, 2013) and Aresta and Dibenedetto (2010) have proposed that production could approach 600–700 Mt in 2020 and 3,000–4,000 Mt by 2050. However, while aquatic algae production appears feasible, land-based production is a challenge.

Carbon dioxide utilization is not a new technology. CO_2 has been used to produce urea for many decades. Currently, CO_2 utilization processes such as urea and methanol production use 122 Mt of CO_2 annually as seen in **Table 2** [adapted from Aresta et al. (2013)]. This by far exceeds the current amount of CO_2 captured by CCS which is 26.6 Mt/year.

COMPARING APPROACHES TO CO_2 CAPTURE, STORAGE, AND UTILIZATION TECHNOLOGIES

To date, there have been few studies on the whole systems, and in particular there are no comparative studies between the complementary CO_2 post-emission handling technologies. To consider a relative assessment, we have made a number of assumptions in order to simplify the argument starting from a common input. We have assumed that the CO_2 supply originates from a power generator or an industrial emitter and that the CO_2 is captured and concentrated on site to produce a common CO_2 stream entering the processes compared. In all cases, the captured and purified gas will need to be transported to its final destination. For the purpose of comparison, it is assumed that this will be using a dedicated pipeline. For CCS and EHR, the pipeline is necessary between the capture and the storage site. For CDU, it is proposed that a spur on the pipeline can take a slipstream from the main flow to be diverted to the chemicals or synthetic fuels plant. Of course, ideally the CDU plant would be situated close to the capture plant in order to reduce costs. Therefore, as these processes are common, we neglect the GHG emissions in the early part of the supply chain up to and including the transportation of the CO_2 from the capture step. We then compare the net CO_2 sequestration at the storage site as the first end boundary condition and then on consumption of the product produced (fuel combustion) as the second end boundary condition.

In order to compare CCS, CO_2-EOR, and CDU, it is necessary to define a functional unit for the analysis. As there is no product in CCS then an initial functional unit has been chosen to be 1 m^3 CO_2 input into a process. This can be later scaled or transferred to an alternative functional unit depending on the exact process. For CCS and CO_2-EOR, 1 m^3 of the gas is injected under supercritical conditions into a cavity of 1 m^3. We have taken the density of CO_2 to be that of the super critical fluid at the critical point, which is 469 kg m^{-3}. In CCS, the cavity (or pores) is regarded as being empty, or filled with saline water, while in CO_2-EOR, the cavity contains crude oil with an average density of 900 kg m^{-3} and an average molecular formula equivalent to $C_{19}H_{40}$ (248 kg $kmol^{-1}$). For CDU, 1 m^3 of CO_2 is reduced with hydrogen in a power to liquid process to yield nonadecane ($C_{19}H_{40}$), analogous in molecular weight to the crude oil above.

In the case of CCS, the CO_2 is simply injected into the cavity under supercritical conditions. The density of $scCO_2$ is taken to be 469 kg m^{-3} and so 469 kg are sequestered. Therefore, the net sequestration of CO_2 is +469 kg. For CO_2-EOR, there are a number of scenarios depending on the miscibility of the CO_2 with the oil or gas. We will consider two scenarios that liberate the trapped oil. Firstly, this may result from an immiscible injection process whereby 1 m^3 of oil is displaced by 1 m^3 of $scCO_2$. This will liberate 900 kg of crude oil at the well head, while 469 kg CO_2 are sequestered. Again there will be a net sequestration of CO_2 at the well head of +469 kg. We also consider a miscible mixing process whereby there is complete mixing to give 50% CO_2 and 50% crude oil. Assuming ideal mixing, 469 kg CO_2 and 900 kg oil will mix to

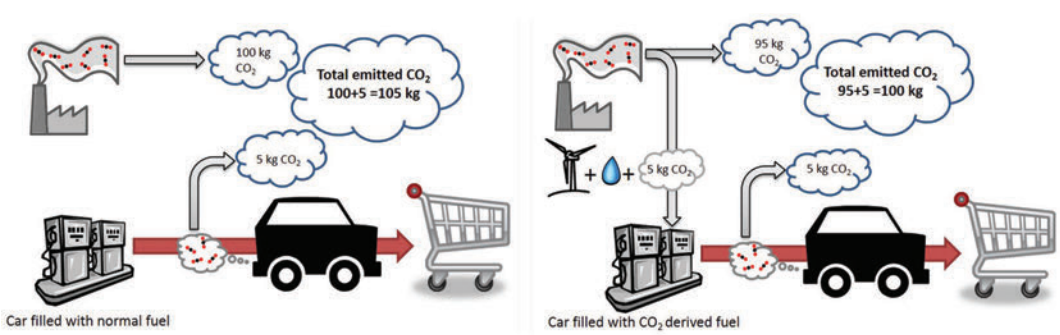

FIGURE 2 | The concept of avoided carbon. Emissions based on no carbon capture and fossil-derived transport fuel (left) and no capture but 5% conversion of industrial emissions into synthetic transport fuel (right).

Table 2 | Current CO_2 utilization technologies and forecasts for 2016 [adapted from Aresta et al. (2013)].

Compound	Total production by all methods (Mt/year)	CO_2 used in CO_2-derived production (Mt/year)	2016 Total production forecast (Mt/year)	2016 CO_2 needed (Mt/year)
Urea	155	114	180	132
Methanol	50	8	60	10
DME	11.4	3	>20	>5
TMBE	30	1.5	40	3
Formaldehyde	21	3.5	25	5
Polycarbonates	4	0.01	5	1
Carbamates	5.3	0	>6	1
Polyurethanes	>8	0	10	0.5
Acrylates	2.5	0	3.0	1.5
Inorganic carbonates	200	*ca.* 50	250	70
Total		180		256

Table 3 | Net sequestration of CO_2 by the different mitigation technologies for "cradle to gate" analyses.

Process	Net CO_2 sequestered or used/kg m^{-3}	Product
CCS	469	No product
Immiscible CO_2-EOR	469	Crude oil
Miscible CO_2-EOR	234.5	Crude oil
CDU 100% conversion	469	$C_{19}H_{40}$
CDU 70% conversion	328	$C_{19}H_{40}$
CDU 50% conversion	234.5	$C_{19}H_{40}$

give a 2 m^3 mixed solution. A 1 m^3 sample will therefore contain 234.5 kg CO_2 and 450 kg crude oil. The mixture released at the well head will therefore also contain 450 kg oil and 234.5 kg CO_2 will be either released to the atmosphere or re-injected into the well in a recycle process. However, to keep boundaries consistent, we will take this 234.5 kg CO_2 as being non-sequestered. The amount of CO_2 remaining in the well will be 234.5 kg and the net sequestration will be +234.5 kg CO_2.

For CDU, we also make an extreme assumption: complete conversion of CO_2 to -CH_2- by catalytic Fischer-Tropsch-type reduction. Again, the functional unit is 1 m^3 CO_2 (469 kg, 10.66 kmol), which is converted to 10.66 kmol -CH_2- units, or 0.65 kmol $C_{19}H_{40}$ molecules. For complete conversion, the net amount of CO_2 sequestered is 469 kg. We can also consider other lower concentrations whereby 70% conversion would produce 0.46 kmol product and 50% conversion would produce 0.33 kmol product. The net capture is defined as the amount entering the system minus the amount emitted. For 100, 70, and 50% conversion, the net amount of CO_2 sequestered is therefore 469, 328, and 234.5 kg, respectively. The scenarios are summarized in **Table 3**.

As stated, this gives a "cradle to gate" analysis that does not take account of any emissions originating from the product. One of the concerns raised against CDU is that any fuels produced will be eventually re-released to the atmosphere. While this is certainly true, any fuels originating from EOR needs to be considered similarly. Obviously, there will be no emissions as a result of CCS so the net emissions reduction will remain at 469 kg. However, CCS does incur considerable CAPEX and OPEX costs through capture and pipeline construction to the storage site; and solvent regeneration, replacement, and gas compression, respectively. If we consider that immiscible EOR releases 900 kg crude oil with an average molecular weight of 248 kg $kmol^{-1}$ ($C_{19}H_{40}$), then the production is 3.63 kmol. On complete combustion, each molecule of oil will release 19 molecules of CO_2 (69.4 kmol) with a mass of 3,051 kg. This has a significant effect on the net emissions. The "cradle to gate" emissions reduction of +469 kg then becomes −2,582 kg emitted once the "cradle to grave" scenario is implemented. For the miscible CO_2-EOR case, the 450 kg oil produced will release 1,526 kg of CO_2 on complete combustion. The "cradle to grave" emissions now become −1,292 kg which is obviously lower than the immiscible case, however less fuel is produced and so lower profit is achieved.

The "cradle to grave" analysis for CDU is interesting. The conversion takes 469 kg (10.66 kmol) CO_2 and converts it to 0.56 kmol (139 kg) $C_{19}H_{40}$. Combustion simply converts this back to 469 kg CO_2 so there is no net emission over the process. Therefore, 469 kg CO_2 are consumed in producing the fuel and 469 kg are emitted through its subsequent combustion, net emissions are zero. However, there is an added bonus, as the CO_2-derived fuel will be used in place of a fossil fuel, therefore giving a net emissions reduction of +469 kg. If the "cradle to grave" scenario is employed, this is much more environmentally benign than either of the EOR processes.

When considering the production of a fuel, it is more usual to define a quantity of the product as the functional unit. In this case, we will define it as 1 t of oil extracted in EOR or 1 t of synthetic fuel produced from CO_2. From CDU, 139 kg synthetic fuel ($C_{19}H_{40}$) is produced from 469 kg CO_2. Therefore, the production of 1 t synthetic fuel consumes 3.37 t CO_2. For immiscible EOR, 900 kg crude oil ($C_{19}H_{40}$) is produced from 469 kg CO_2 and hence 1 t of oil is produced using 521 kg CO_2. This means 6.5 times more CO_2 is sequestered in the CDU process than in immiscible EOR. This is summarized in **Table 4**.

Returning to the database of CCS projects, it can be noted that of the projects in the Operate phase, 11 are EOR projects and 2 are geological storage projects. Based on our calculations above and assuming an immiscible system, these EOR CCS projects would actually result in CO_2 emissions of 128 Mt/year from the combusted oil products. When you then consider the projects in the Execute and Define stages, the situation does improve but not dramatically. In the Execute stage, 6 of 9 projects are EOR resulting in net emissions of 38 Mt/year and in the Define stage, 8 of 14 projects are EOR giving 59 Mt/year CO_2 emitted on the combustion of the produced oil (**Table 5**). Combining all CO_2 produced by combusting the EOR products, we would need over 200 extra geological storage-based CCS facilities to sequester the CO_2 emitted from EOR. This is 18 times the number of geological storage projects planned in these three phases. Obviously, this is far from ideal and is not practically possible. Therefore, it is our opinion that EOR should not be considered as a mitigation technology and instead we should be investing in CDU-based fuels. We acknowledge the

Table 4 | Comparisons of net CO_2 emissions using the CCS, EHR, and CDU strategies discussed.

Process	CO_2 used/kg	Product	Amount of product	Amount of CO_2 released when product combusted/kg	Net CO_2 sequestered or offset/kg
CCS	469	No product	0	0	469
Immiscible CO_2-EOR	469	Crude oil	900	3,051	−2,582
Miscible CO_2-EOR	234.5	Crude oil	450	1,526	−1,291.5
CDU 100% conversion	469	$C_{19}H_{40}$	139	469	469
CDU 70% conversion	328	$C_{19}H_{40}$	97	328	328
CDU 50% conversion	234.5	$C_{19}H_{40}$	69.5	234.5	234.5

Table 5 | Analysis of CO_2-EOR projects and further mitigation requirements needed to handle additional CO_2 emissions.

	Operate	Execute	Define
CO_2 sequestered in EOR (Mt/year)	25.00	7.50	11.46
Volume CO_2 (m^3/year)	50,403,226	15,120,968	23,104,839
Mass crude (Mt/year)	45	14	21
Mass CO_2 in burnt crude (Mt/year)	153	46	70
Total CO_2 emitted (Mt/year)	128	38	59
Amount CO_2 stored in geological storage (Mt/year)	1.6	5.5	12.4
No of CCS geological projects	2	3	6
Average geological storage per project (Mt/year)	0.8	1.8	2.1
Total number extra geological storage projects needed to remove EOR-CO_2	160	21	28

economic potential of EOR versus geological storage CCS and therefore why it is an attractive option. However, when discussing CO_2 mitigation, EOR simply cannot be considered a mitigation strategy when a "cradle to grave scenario" is applied. The market for hydrocarbon fuels is large, and economics drives the push for extracting evermore harder to reach oil sources, but this just further exasperates our CO_2 problem. The conversion of CO_2 into synthetic hydrocarbon fuels would satisfy our demand whilst limiting the environmental consequences.

CO_2 UTILIZATION POTENTIAL

As described above, EHR/EOR will result in more CO_2 emissions. CCS will reduce emissions but at a cost and the projected rate of deployment is modest. But what about CDU?

Though significant amounts of CO_2 are being currently utilized, the potential is much higher. CO_2 can be used as the carbon source in a wide variety of products and hence the volume of CO_2 that can be utilized is high. In **Figure 3**, we have produced a scenario for CO_2 utilization, which incorporates current uses such as urea production and replaces fossil oils in other processes to produce a small range of organic chemicals, diesel and aviation fuel, methane (synthetic natural gas), and some polymers. The case of urea is interesting. While current processes rely on hydrogen derived from fossil fuel sources, there is a drive to produce "green" hydrogen through the electrolysis of water using excess intermittent renewable energy supplies such as wind and solar. In the final section, we will consider the practicality of such an approach. We have also included the mineralization of industrial wastes providing long-term CO_2 sequestration and construction materials. The potential for the creation of mineralized products from CO_2 is in reality much higher, however this often involves mineralizing substances such as olivine or serpentine, which will first have to be mined. Therefore, to negate environmental impacts of mining, we have only included the mineralization of waste such as fly ash, bauxite, and steel slags. Mineralizing these wastes to turn them into commercially useful construction materials provides a favorable greener alternative to traditional disposal and should be prioritized in CO_2 mineralization.

The graph in **Figure 3** proposes the quantity of CO_2 that could be utilized at different market shares based on current levels of production and compares this against CO_2 reduction targets for the EU and the World in CCS, and EU and USA overall CO_2 reduction targets. It can be observed that only producing 10% of each product would make significant inroads into the EU CCS target or exceed it. The potential for diesel, aviation fuel, and methane (as a synthetic replacement for natural gas) is high due to the large quantities consumed per annum. As discussed previously, although the majority of these products are produced to provide energy *via* combustion, hence re-releasing the CO_2, the net reduction in CO_2 emitted due to switching from fossil sources will be significant. A scenario whereby 100% of the current urea, 20% of specific chemicals, 30% waste mineralization, 20% of specific polymers, 5% diesel and aviation fuel, and 10% methane are produced using CO_2 is shown in the graph in **Figure 3**. This scenario (purple bar) represents a realistic yet challenging estimate for CDU deployment by the year 2030. In this scenario, 1.34 Gt of CO_2/year would be utilized. This amount of CO_2 is equal to 95% of the CO_2 that must be reduced in the EU by 2030, and is equivalent to 83% of the world target for CCS by 2030.

However, one question that must be addressed is how realistic is the possibility of CDU deployment on this scale. Worldwide there are a number of commercial and pilot scale CDU projects. Carbon Recycling International in Iceland is producing 5 million liters (950 t) of renewable methanol per annum from CO_2 accounting for 1.5% of world production. The company has plans to expand production to bring renewable methanol to a global market outside Iceland in partnership with Methanex (the world's largest methanol supplier). Bayer Material Science has recently invested €15 million in the construction of the world's first commercial

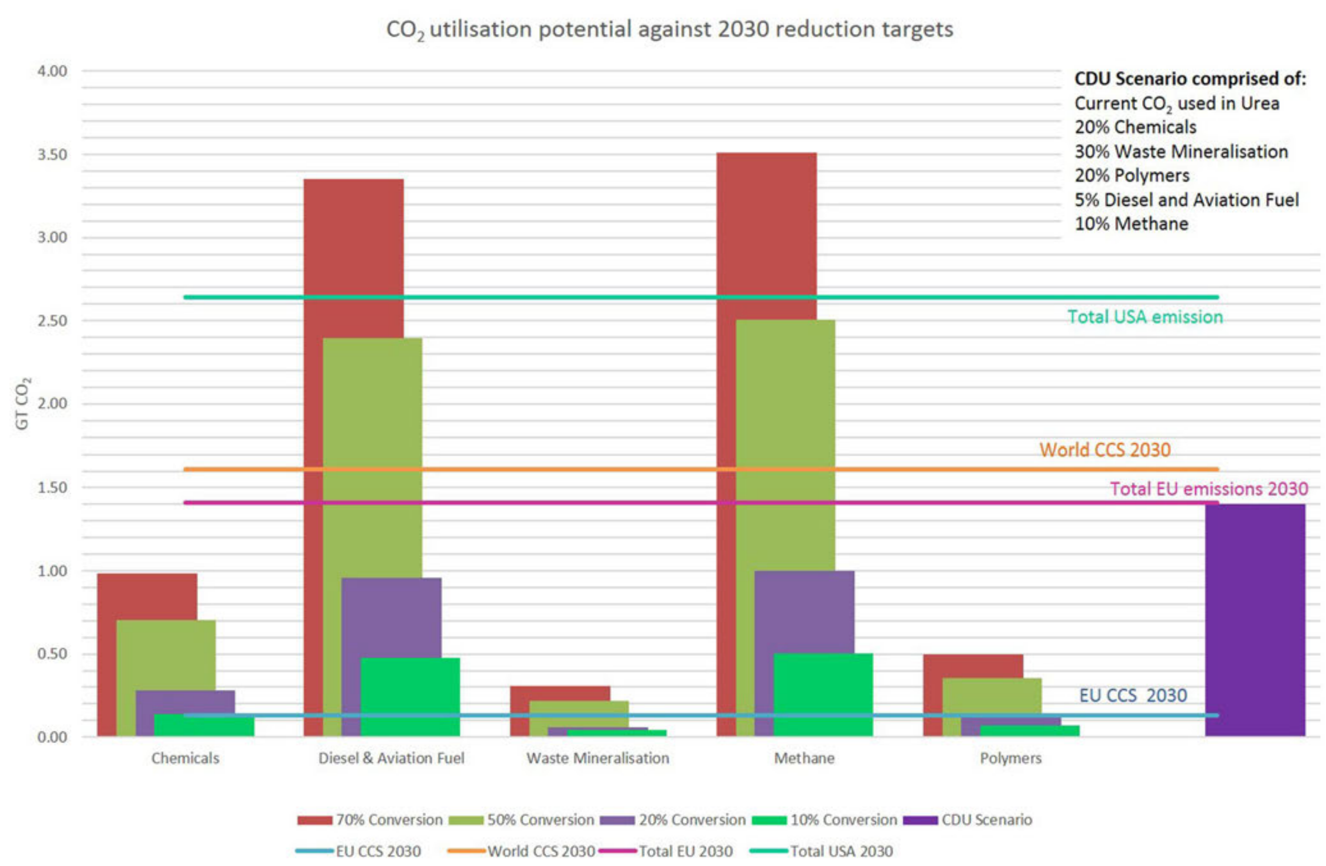

FIGURE 3 | Replacement of fossil-derived chemicals and fuels by CDU replacements assessed against CO_2 emission reduction targets in the EU, USA, and globally.

plant to produce polyols from CO_2 as a precursor for CO_2-based polyurethane foams. Based in Dormagen, the plant will manufacture 5 kt/year with the aim to have the first commercial CO_2-based polyols on the market by 2016. Novomer, a USA-based company, has commercialized a range of CO_2 polyols under the trade name Converge®. The polymers contain up to 50% CO_2 by mass and are based on a proprietary catalyst system that produces low-cost polyols and polymers for a wide variety of applications. They currently have a 5-kt/year of capacity and have begun a plant design process to expand to make 100 kt for 2017. KOGAS DME Activities for Commercialization (2011) in Korea has been manufacturing DME from CO_2 since 2000 on demonstration and pilot scale plants. KOGAS' next phase will be a commercialized process producing 3,000 t/day of DME. The Jiangsu Jinlong-CAS Chemical Co. Ltd. in Taixing, China uses waste CO_2 from ethanol manufacture to produce polypropylene and polyethylene carbonate polyol to be used as flame retardant exterior wall insulation. By 2015, it aims to have expanded production to utilize 80 kt/year CO_2. The Asahi Kasei Chemicals Corporation's phosgene-free process to manufacture polycarbonate from CO_2 has been licensed to multiply companies. Five-hundred ninety-five kilotonne per year of polycarbonates are manufactured annually using this green process resulting in a reduction in CO_2 emissions of 102 kt/year. This is equivalent to the proposed full global CCS plant capacity by 2020.

Skyonic has opened its first commercial CO_2 utilization plant in San Antonio. The plant directly captures 75 kt/year CO_2, which is used to manufacture salable products such as sodium bicarbonate and sodium carbonate, and bi-products such as bleach and hydrochloric acid. Skyonic have calculated along with the CO_2 utilized in the process, an additional 225 kt of CO_2 will be offset by the production of green by-products. These examples show that CO_2 utilization is becoming a commercial reality, with potential to make a significant difference in the amount of CO_2 emitted and in creating a greener, sustainable chemical industry.

CONSIDERATION OF CDU AND CCS AT A POINT SOURCE EMITTER

The UK has announced two potential CCS facilities at power stations in Yorkshire (White Rose Project, Drax) and Scotland (Peterhead). The former is an oxy-fuel facility while the latter is a post-combustion amine capture facility. To put the argument in favor of CDU into context, we will consider the Peterhead facility as a base case. The plant will capture part of the total plant emissions, 1 Mt/year CO_2, which will then be piped to a geological storage site in the North Sea. So how does that 1 Mt/year storage capacity compare with what could be achieved through CDU?

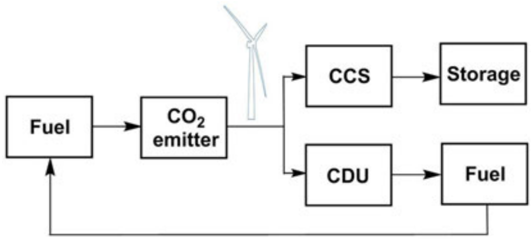

FIGURE 4 | Schematic representation a CDU recycling process in a combined CCS-CDU capture system, using wind energy to power the process.

The Peterhead plant has a proposed CO_2 capture capacity of 1 Mt/year, which equates to 2.74 kt/day or 114.2 t/h. So how much hydrogen is needed to convert this to synthetic oil? If 1 Mt/year CO_2 were to be converted into synthetic oil, this would produce 0.30 Mt/year product as the functional unit of 1 t synthetic oil would require 3.37 t CO_2. So each day, 274 kt CO_2 would be captured by the plant and this would be reduced to produce the synthetic oil. To a good approximation, each CO_2 molecule is reduced to one -CH_2- sub-unit and two molecules of water. Therefore, for each CO_2 reduction, three equivalents of hydrogen are needed. This means that 44 t CO_2 will require 6 t hydrogen to produce 14 t of equivalent -CH_2- sub-unit and 36 t water. Therefore, 1 Mt CO_2 will require 0.136 Mt/year H_2 to produce 0.30 Mt/year synthetic oil.

Over a 24-h period from 20:30 on 16 December, 2014 to 20:30 17 December, 2014, the average UK wind generation was 114,170 MWh, representing 12.1% of the UK energy mix. If all the wind energy were converted to hydrogen through water hydrolysis, how much would be produced? Boretti (2012) has reported that the production of 1 kg of hydrogen requires 53 kWh electricity to power the process. This is equivalent to 53 MWh/t H_2 produced, which is 0.019 t (19 kg) H_2/MWh. Therefore, in the generation period described 114,170 MWh would produce 2,169 t H_2. If Peterhead is capturing 114.2 t/h CO_2, this will need 15.6 t/h H_2. Expressed as a total of the wind generation, this is 0.7%. Therefore, diverting less than 1% of the renewable wind energy to synthetic oil production would remove the need for the captured CO_2 to be sequestered geologically. Of course, there are times when there is insufficient wind, or base line power consumption is high, so that this renewable energy cannot be diverted (Hall et al., 2014). However, there are also times when wind production exceeds baseline demand, for example in summer. While it is usually customary in such cases to turn off the wind turbines, we suggest that it is more environmentally and economically beneficial to utilize that excess energy to store it chemically for future use. This provides an alternative for just CCS. By adding CDU, this allows capture capacity to be diverted from a waste stream to a product stream, thereby generating income; or adding additional capacity to capture more CO_2 and ultimately increase the environmental credentials by avoiding more fossil fuel use. This is summarized schematically in **Figure 4**, which shows how a carbon cycle can be developed as a means for seasonal energy storage. If the fuel is diverted to the transport sector, then the additional use of direct air capture of CO_2 must also be considered.

CONCLUSION

In conclusion, although geological CCS will provide a reduction in the CO_2 emitted to the environment, the projected capacity of CCS projects is just not on a scale compared with the CO_2 reductions that are needed. Twenty-two CCS projects are described as being in the Operate or Execute phase with a projected capture capacity of approximately 40 Mt/year by 2018. However, the IEA target for CCS for 2020 is 60 Mt/year (Energy Technology Perspectives, 2014) and of these 17 are EHR projects which when considering net "cradle to grave" emissions will produce further CO_2 emissions of 166 Mt/year. In comparison CO_2 utilization projects are in operation, are growing in deployment and are providing a net reduction in CO_2 both by utilizing CO_2 in production and by providing a new fossil-free source for these products. It can be argued that in terms of emissions EHR is better than non-EOR oil production as some CO_2 is sequestered. However, when one considers the large amounts of CO_2 produced when oil is combusted, we would have a far greater chance of limiting climate change if we switch from oil-based fuels to CO_2 utilization-based synthetic fuels. However, CDU capacity is currently higher (180 Mt/year) that operational CCS capacities (26.6 Mt/year) and utilization is predicted to reach 256 Mt/year by 2016, again much higher than CCS. This trend is likely to persist as more CDU processes move from laboratory to demonstrator scale.

Furthermore, CDU can provide carbon-neutral fuels and other products that while net sequestration may be lower than in the case of CCS do add valuable products into the economy. EHR will remain a means for economic benefit but cannot be considered as a mitigation technology as it ultimately emits more carbon dioxide than it sequesters through product use. If immiscible EHR is compared against mitigation potential for CDU and CCS, the figures are +2,582:0:−469 respectively where a negative value represents sequestration and a positive value an emission.

Carbon dioxide utilization will provide much needed additional capacity, with profit, in the move toward a low carbon economy. CO_2 is used as a resource, not a waste. Like CCS, it should be regarded as one of the key emissions mitigation technologies in the fight against climate change. However, the same cannot be said of EHR which will ultimately lead to net CO_2 emissions.

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6 Integration of techno-economic and life cycle assessment: Defining and applying integration types for chemical technology development

This chapter comprises of a reprint of a research paper by Wunderlich, Armstrong, Buchner, Styring and Schomäcker (2021). The supplementary information for the paper can be found in the Supplementary Material section at the end of the thesis. The author contributions are as follows:

Johannes Wunderlich: Conceptualization, Methodology, Investigation, Data curation, Writing - original draft, Writing – review & editing, Visualization, Project administration.

Katy Armstrong: Conceptualization, Methodology, Investigation, Data curation, Writing - original draft, Writing - review & editing.

Georg A. Buchner: Conceptualization, Methodology, Writing – original draft.

Peter Styring and Reinhard Schomäcker: Supervision.

This chapter explores the necessity for integrating different assessment types to avoid conflicting conclusions from individual assessments. Within CO_2 utilisation the potential of a new technology to deliver environmental impacts can be hindered by unfavourable economic assessment. By integrating the two assessment types and by allowing further expansion to include social impacts (see chapter 7) hotspots can be identified to expedite technology development through enhanced decision making. The work identifies that a single one-size-fits-all methodology for integration is not suited to the varying goals for studies. Therefore, a framework for guiding practitioners through integrated assessment choices is presented. Thus enabling effective methodological choices to be made dependent on the goal, available data and resources.

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Integration of techno-economic and life cycle assessment: Defining and applying integration types for chemical technology development

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ABSTRACT

Both an environmental and an economic assessment are needed to judge the potential of sustainable chemical technologies. However, decision makers may be challenged by conflicting conclusions. The integration of life cycle assessment (LCA) and techno economic assessment (TEA) can enhance decision making, as integrated assessments provide more information than a simple reporting of separate TEA and LCA results. The analysis of integration approaches reveals a lack of consistency in terms of defining criteria and methodological aspects for integration. A gap remains where guidance for practitioners is needed on how to select a suitable integration type for their different purposes. To fill this gap, we conclude that a one size fits all solution of integration cannot adequately serve all purposes along the technology development phases. Therefore, a framework to guide through integration in three distinct parts is proposed. In Part I, a four phase approach for every integrated assessment to link the results from TEA and LCA is defined. Part II develops three integration types classified by their core characteristics: qualitative discussion based (Type A), quantitative combined indicator based (Type B), and quantitative preference based (Type C). Finally, in Part III, a step by step method to select the appropriate integration type according to the assessment purpose, while considering restrictions imposed by technology maturity and resource availability is introduced. Thus, the framework is a basis for increasing the number of integrated assessments by guiding practitioners towards tailored studies.

1. Introduction

1.1. General principles of techno economic assessment and life cycle assessment

The call for sustainable processes within the chemical industry necessitates measures to ascertain economic viability and the level of environmental impacts (Zimmerman et al., 2020). Despite the importance of social impacts as third sustainability dimension, these are left outside the scope of this work which focuses on established practices in research and development. Techno economic assessment (TEA) and life cycle assessment (LCA) are commonly used methodologies to assess underlying criteria individually. However, decision making in technology development should not be made from either the economic or the environmental perspective alone (Norris, 2001a). Sound decision making requires an understanding of the trade offs which is not fully developed if only a separate reporting of TEA and LCA results is available. In contrast, integrated assessments intend to derive combined goal driven insights by specifically describing the interdependencies of the indicator results (van der Sluijs, 2002). Therefore, in this work, integration of TEA and LCA is defined as the selection and processing of available information from both assessments to prepare a meaningful interpretation shining light on how TEA and LCA results are linked.

TEA and life cycle costing (LCC) (Hunkeler et al., 2008; Swarr et al., 2011) can be defined as methodology frameworks that provide systematic approaches for assessing the economic viability of a technology as depicted in Fig. 1. TEA is typically limited to an inherent investor perspective with cradle to gate system boundaries, whereas LCC's inherent perspective aims at cost analysis

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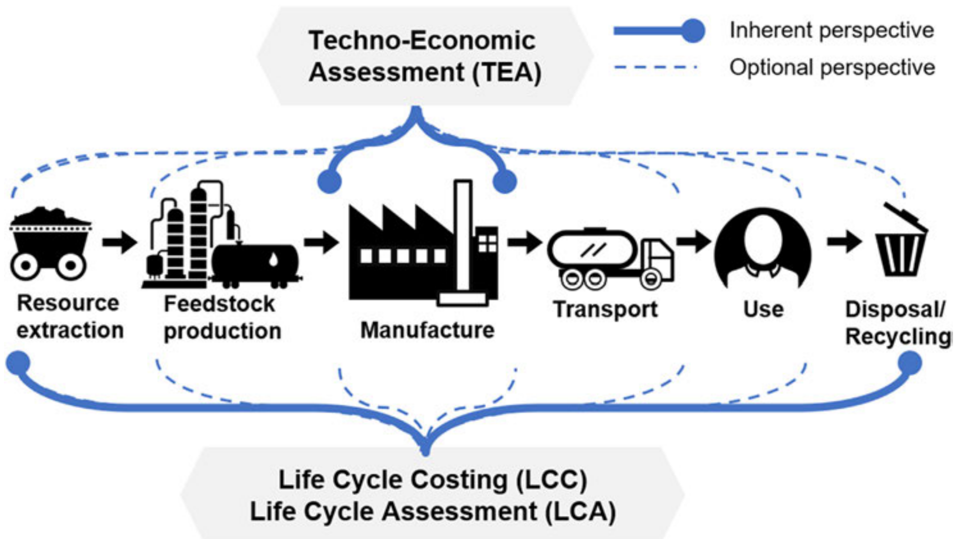

Fig. 1. Product life cycle depicting inherent perspectives of TEA (investor-perspective within manufacturing gates) and LCC and LCA (full life cycle perspective for all actors); both TEA and LCC can equally cover any combination of stages.

along all life cycle stages of a product (Miah et al., 2017). Both TEA and LCC methodologies can be adapted to include further optional perspectives. This paper focusses on TEA because of its strong relation to technology development in the chemicals industry (a detailed methodological comparison of TEA and LCC is provided in the Electronic Supporting Information). Integral parts of TEA are cost and market analysis to provide data for profitability indicators. Optionally, TEA entails the reporting of selected technical parameters in the context of technology development. TEA methodology is not standardized and requires to be tailored to each case. However, a four phase approach guiding the assessment has been proposed that is also inherent to LCA (Buchner et al., 2018; Zimmermann et al., 2020a). LCA methodology is standardized by ISO 14040/44 (International Organization for Standardization [ISO], 2006a, 2006b). Further guidance for LCA is available, for example in the ILCD handbook (European Commission Joint Research Centre Institute for Environment and Sustainability, 2010) and the handbook on life cycle assessment (Guinée et al., 2002). Due to methodological overlaps with TEA, the focus in this paper lies on the type 'process LCA' (Guinée et al., 2011) which will be referred to as 'LCA' only. When applying TEA or LCA to technology development, methodological choices should match data availability within the three innovation phases: applied research, development and deployment (RD&D). The technology maturity along RD&D can be expressed by nine technology readiness levels (TRLs), reflecting the available information according to specific criteria (Buchner et al., 2019).

1.2. Concepts for combining economic and environmental assessment and remaining gaps in literature

Norris (2001a, 2001b) highlights the need for private industry to take into account economic implications when applying LCA to characterize relationships and trade offs between both dimensions. The work informs about the successful implementation of the concept of total cost assessment (TCA) within several industrial companies (CWRT, 1999). TCA aims at including often hidden internal, and optionally external, cost items incurred by environmental and health related issues into cost estimation practices of companies. The method intends to consider the perspectives of various stakeholder groups and to include costs of manufacturing, future and contingent liability costs as well as external costs borne by the society including the deterioration of the environment. By methodologically linking data from cost analysis with life cycle assessment results, companies are reported to benefit from better informed investment decisions. However, a discussion of suitable ways for interpretation of the aggregated economic and environmental results is not presented.

Azapagic et al. (2006) focus on process design stages and highlight the importance of a suitable indicator selection if multiple target audiences with conflicting interests need to be informed by the integrated assessment. The authors propose to integrate environmental and economic results in one indicator, representing environmental impact per value added. The method aims at applying the tools at all life cycle stages, however, the authors acknowledge that most assessments are limited to the plant operation. Santoyo Castelazo and Azapagic (2014) extend their integration approach by presenting a decision support framework that requires a multi criteria decision analysis allowing to include preferences.

Life cycle sustainability assessment (LCSA) has been introduced as a broad framework to combine models for economic, environmental and social assessments (Finkbeiner et al., 2010; Minkov et al., 2016). Guinée et al. (2011) argue that LCSA is a form of integrated assessment as defined by van der Sluijs (2002), because it serves the intention of combining, interpreting and communicating interdisciplinary information from at least two sustainability dimensions. Miah et al. (2017) consider LCSA to be an overarching framework that may not be suitable for decision makers focusing on TEA and LCA due to the required information from additional assessments.

Hoogmartens et al. (2014) include social life cycle assessment (SLCA) to cover all sustainability dimensions. Along with explaining the linkages within the complementary methods of their framework the authors acknowledge that more comprehensive tools need to be developed, as complexity in methodological choices adds to confusion among practitioners, for example, if trade offs call for conflicting actions.

Miah et al. (2017) classify six types for integrating different aspects of LCC and LCA. Based on the selection of specific methods, the authors suggest a hybridized framework with four iterative stages. Despite providing a decision tree, the framework implies a one size fits all solution covering all identified types that would result in choosing a similar integration approach across all possible assessment goals.

Thomassen et al. (2019) propose a prospective 'environmental techno economic assessment (ETEA)'. Based on TRLs, the authors summarize streamlining strategies for different maturity stages, namely, qualitative methods for TRLs 1–3 and quantitative methods for TRLs 4–9. The dichotomy of qualitative vs. quantitative methods is the only presented difference in the way studies are integrated; the remainder of the ETEA methodology affects calcu lations within every single assessment. Harmonization and trans parency of TEA and LCA regarding data and scope definition is discussed as the leading criterion for integration.

Ibánez Forés et al. (2014) analyzed the stages of decision making in technology assessment with a focus on how to select criteria from multiple perspectives. The authors point out, that in about one third of the reviewed studies the decisions are derived directly from the indicators by numeric or graphic means. In the remaining part, a form of multi criteria decision analysis is applied to aggregate the indicators.

The discussed literature currently presents a variety of per spectives on which are the key steps for combining economic and environmental assessments. For example, some studies focus on the step of selecting appropriate criteria, whereas others discuss integration in the light of newly combined indicators or the inclu sion of preferences via multi criteria decision analysis. Further more, a number of studies are limited to a rigid methodology for integrating TEA and LCA that need to be compliant with an over arching framework, such as LCSA or TCA. While the suitability of each of the frameworks for their particular purpose is acknowl edged, these can be considered as top down solutions that each do not cover the entire sphere of potential integration purposes. There is a lack of guidance for selecting an appropriate integration approach from these methods. Here, the knowledge gap remains in how practitioners can approach an integration of TEA and LCA from the bottom up to subsequently tailor methodological choices to the decision making problem of the target group. Despite an increasing number of contributions in this field, there is no commonly fol lowed definition of the term integration, nor is the integration of TEA and LCA equally understood as an individual assessment that follows a set of general principles.

1.3. Aim of this work and research methodology

The aim of this work is to design a holistic framework enabling practitioners to select an appropriate approach for integrating TEA and LCA for the assessment of chemical processes. To provide guidance, first a general structure of integrated assessments will be derived, followed by the definition of integration types and the development of a step by step procedure to select a suitable type for different integration purposes. The novel contribution com prises the definition of a set of minimum criteria that have to be met for TEA and LCA to be integrated.

The framework is based on exploratory research conducted in three steps:

1. Explore studies that combine economic and environmental as sessments in technology development,
2. Analyze integration methods to answer the following questions:
   a. What are the core characteristics of the integration methods applied in literature?
   b. How does the underlying integration purpose influence the selection of the integration method?
   c. Which other common characteristics of the objects of anal ysis influence the selection of the integration method?
3. Develop a framework that enables the selection of a suitable approach to integrate TEA and LCA from the bottom up.

2. Analysis of studies combining TEA and LCA

2.1. Methodology of analysis

As described, numerous methodological concepts with different requirements and complexities have been proposed to combine TEA and LCA. However, the question arises as to what methodol ogies are currently applied in practice and which common char acteristics can be derived to guide practitioners in their methodological choice.

To answer this, an exploratory research approach was chosen to analyze academic literature until a theoretical point of saturation was reached (Saunders et al., 2018). Saturation was determined once no further new methodologies or characteristics occurred despite increasing the number of analyzed studies. Studies to be analyzed were randomly selected from a base search to ensure an unbiased representation of the approaches used across academic studies in this area. Random selection was chosen, as it is recog nized that the limitation by criteria such as citation number or publication date may produce biased results. The intention was to avoid overrepresentation of works that are cited based on the technology area investigated and not the assessment methodology applied (focus of this work), or of works that are only representa tive for a limited time frame.

An initial Web of Science search was conducted within the selectable Web of Science categories of 'green sustainable science technology', 'energy fuels' and 'engineering chemical' and the search queries within the title, abstract or keywords of ("LCA" or "life cycle assessment" or "life cycle analysis") and ("TEA" or "LCC" or "life cycle cost*" or "economic"). The results were manually screened to remove papers not within the scope of chemical pro cess technologies, producing a set of 711 papers. From this set, papers were randomly ordered using computer generated random selection. Firstly, each paper underwent further screening to ensure that it contained both economic and environmental assessments and was not of review character, otherwise, they were discarded (>50% of papers were discarded in this manner). Subsequently, the paper was analyzed in detail to ascertain the goals, methodologies used, indicators calculated and style of interpretation. Theoretical saturation of methodologies and characteristics was reached at a sample size of 50 papers. To confirm saturation a set of further 20 papers was analyzed. A summary listing the 70 papers and results of the analysis is provided in the Electronic Supporting Information.

2.2. Identified characteristics of combining TEA and LCA

2.2.1. Purpose

The analysis found that the purpose for combining TEA and LCA can vary substantially, for example:

- separately reporting environmental and economic impacts of a whole process;
- assessing hotspots of a single process (often in comparison to an existing technology);
- assessing alternative options for process design, feedstock or product applications;
- performing non detailed comparisons of different technologies to assess the best fit to the goal.

2.2.2. Approach

No standard approach is observed for combining economic and environmental impacts. In many cases, economic and environmental impacts were reported separately and the purpose of the study did not necessitate linkages between indicators to be explored in detail. Those papers directly comparing alternative technologies tend to use a quantitative method of integrating economic and environmental results, such as combined indicators or multi criteria decision analysis:

Combined indicators are applied for technology comparisons

When combined economic and environmental indicators are calculated, the predominant indicator used is carbon abatement cost which occurs in 11 of the 21 papers calculating combined indicators; for example in Telsnig et al. (2013) and Verma et al. (2015). This is unsurprising due to the impetus on reducing global greenhouse gas (GHG) emissions and economic disincentive mechanisms such as carbon pricing or taxes. Hence, determining the process design option that delivers minimal carbon abatement costs is advantageous both from corporate and policy makers' perspectives. Applied as a useful comparison method, a wider range of combined economic indicators is suggested in Mata et al. (2015) and Halog and Manik (2011).

Multi-criteria approaches

30 papers use a multi criteria decision analysis (MCDA) or multi objective optimization (MOO) approach for the integration of the economic and environmental results to enable preference based weighting and aggregation of environmental and economic impacts; for example García et al. (2014) and Tock and Maréchal (2015). Methodologies observed range from simple ranking systems that aggregate the results to select the preferred alternative (MCDA), to mathematical optimization techniques that identify a set of optimal alternatives (MOO). In the sample, MOO is most commonly applied for Pareto curves (Marler and Arora, 2004) which present a set of scenarios that each cannot be improved in one dimension without worsening the other. MCDA (Velasquez and Hester, 2013) is mostly applied *via* analytical hierarchy processes (AHP) by using pair wise comparisons to estimate criteria weights. As methodology choice remains a difficult task for the practitioner, frameworks have been suggested to assist selection, for example, Guitouni and Martel (1998) and Wątróbski et al. (2019). A small number of papers present examples for applying a specific MCDA approach within a larger framework to support decision makers (Gargalo et al., 2017; Halog and Manik, 2011; Zhang et al., 2016). Some papers employ a combination of combined indicators and MCDA methods; for example Gargalo et al. (2017), Reich (2005), Tock et al. (2015) and Bernier et al. (2010).

2.2.3. Further characteristics

Overall, a number of common characteristics were identified across the analyzed literature:

Goals of the assessments are generalized

It was observed that in 44 papers a general type of a combined economic and environmental goal is stated, often in the style of 'the aim of the study is to evaluate the economic and environmental impacts of the process'. This type of generalized goal does not elucidate whether the interactions of the economic and environmental impacts will be discussed, nor does it provide significant detail as to unambiguously describe the goal as required in ISO 14040 for LCA. The remaining papers state a combined goal in the introduction to the work and further define separate sub goals before the individual economic and environmental assessment sections of the paper. Examples of this include Thomassen et al. (2018) and Chao et al. (2019). Largely, these LCA/TEA sub goals are more detailed tending towards ISO 14040 requirements. However, a statement of the intended audience or stakeholders for the study is not common, except for some cases such as Khatiwada et al. (2016).

Discussions of the linkages between environmental and economic impacts vary

The analysis highlighted that there is variation in the discussion of the linkage between economic and environmental impacts, and that sensitivity and uncertainty analysis are not applied uniformly. In 27 of the 70 papers, the impacts are interpreted separately after their individual analysis and their interactions with each other are not expressed beyond a couple of sentences; for example, Pastore et al. (2016), Di Maria et al. (2018), García Velásquez and Cardona (2019). Papers that include MCDA were predictably found to have the most detailed interpretation of the linkages, as this is the objective of such analysis. These papers use graphical representations, diagrams, matrices, and tables mixed with written discussion to show the relationship between the economic and environmental indicators; examples are Tock and Maréchal (2015) and Lu and El Hanandeh (2019).

Technology readiness level (TRL) concept is not widely used in scope definitions

The maturity of the technology has a significant impact on the quality of the data and uncertainty of the analysis and therefore a definition of the assessed technologies maturity is of great benefit when determining how integration can be applied (Buchner et al., 2018; Moni et al., 2020; Zimmermann et al., 2020a). Only three mentions of the TRL concept were found throughout the analyzed papers. Maturity of the technology was discussed in 17 of the papers, using terms such as 'immature' (Tang and You, 2018) and 'emerging' (Halog and Manik, 2011). However, these terms are broad and could imply the whole range of development stages from laboratory to demonstration scale. Therefore, it is surprising that a clear definition of the maturity of the assessed process by a standardized methodology, such as TRL, is not included. The TRL concept is widely recognized and often used in industry and scientific mechanisms such as EU Horizon 2020 since 2014; as 46 of the papers have been published since 2014 it is unexpected to not see it more widely applied in academic research.

3. Development of the integration framework

3.1. Conceptualization

A major finding from the literature analysis is the great variety of approaches to combine economic and environmental assessments. However, these can be characterized and sorted into a number of discrete integration activities. In general, the activities can be differentiated into qualitative or quantitative approaches. It was found that the goal of the study affects the depth to which TEA and LCA are combined, indicating the importance of articulating this clearly. Furthermore, the literature review of current frameworks showed that practitioners planning the integration of TEA and LCA lack early guidance as to whether a qualitative or quantitative approach is suitable for their individual purpose (goal). Hence, a framework is derived to provide a systematic pathway to find the fitting integration activity. This equips practitioners with key underlying principles and enables them to manage the variety of methodological choices. The framework is derived consisting of three parts:

- **Part I** defines key aspects of integrated assessment,
- **Part II** defines integration types,
- **Part III** presents an approach to select a suitable integration type.

As the specific terminology related to the topic of integration varies in the literature, the relevant terms used in this paper are described in Table 1.

3.2. Part I – key aspects of an integrated assessment

The purpose of integration is to give indications for a subsequent decision making step within the overall progression of technology development and assessment. Thus, the focus must be on the interaction between the TEA and LCA indicators. Integration can be operationalized in the form of an individual, overarching assess ment combining subordinate TEA and LCA. Such integrated as sessments can be approached with the same four phases (I IV) that apply to single TEAs or LCAs as depicted in Fig. 2: Goal and Scope (I), Inventory (II), Impact Calculation (III), Interpretation (IV). Within this multi layer assessment structure, integration is superordinate, relying on a well balanced subordinate TEA and LCA to feed the inventory of the integrated assessment. Thus, whether the resulting integration complexity is high or low is inter dependent on what can be provided by the scopes of TEA and LCA. Between the indi vidual phases, iterations are possible to refine the assessment. After completing the assessment, the interpreted results are used to support decision making which can affect different areas, such as process design or investments into specific technologies, and potentially start a new assessment iteration. Key aspects of the four phases of integrated assessments will be discussed in the following paragraphs.

Goal and Scope (I). The integration goal needs to clearly state the motivation for the integration of TEA and LCA and articulate the decision problem. This should include a detailed description of the purpose that drives the practitioner. A statement about the type of expected results and how these will be used helps methodological choices in the scope. In this regard, it is important that the goal reflects the motives and distinct roles of commissioner, practitioner and target audience of the integrated assessment. Three different relationships of these roles can be identified as depicted in Fig. 3. Each relationship is defined by a different interdependency of the roles, which needs to be accounted for when setting the integration goal. This signifies that two assessments of the same technology can differ when the practitioner is influenced by the commissioner in terms of limited resources or by the target audience regarding the leading question and how to properly present results. For example, in a company, a typical goal of the senior management (joint role of target audience and commissioner) could be the ranking of two investment alternatives. In this case, an engineer (integration practitioner) is tasked to enable a quick decision by limiting the integrated assessment to a set of two weighted criteria. Prior to this point however, the engineer was solely responsible for developing and assessing the alternatives (three joint roles), and therefore selected a different integration approach that supported the detailed analysis of hotspots following a multitude of different criteria. In this regard, the integration type selected should reflect the individual character of the integration goals.

As the integrated assessment depends on the underlying char acteristics of the subordinate TEA and LCA, further sub goals can be defined to add direction to these studies. The integration scope operationalizes the goal by defining the integration type and the data from TEA and LCA needed for the integration. Dependent on the aim of the integration, it is not required that subordinate TEA and LCA have been carried out simultaneously and on the same base data. Therefore, the integration scope needs to define the allowed uncertainty caused by the level of data alignment. It is key to understand the scope definition of each study to judge the level of their alignment regarding system boundaries, selected bench mark for comparison and underlying technical data in the form of material and energy flows. Differences in scope can affect choices in how an integration can be carried out.

Inventory (II). The integration inventory largely consists of the (intermediate) results of the subordinate assessments, at least one TEA and at least one LCA which can be either conducted in parallel as one overall study or in separate studies The integration approach set in the goal and scope guides the data selection in terms of data type, level of detail and alignment. If the required data cannot be provided, either the subordinate assessments need to be adapted accordingly, or the integration goal needs to be adapted to the available data.

Impact Calculation (III). The impact calculation phase serves to select and optionally transform the TEA and LCA indicator results from the integration inventory to prepare the subsequent inter pretation. In its most basic form, this is the core activity of quali tatively selecting and presenting all information to be discussed, thus narrowing down the inventory. If the discussion is not suffi cient for the integration goal, further processing of these indicators to new combined indicators or MCDA can be included. Combined indicators merge criteria of TEA and LCA, thus creating a new, combined criterion, for example, the calculation of CO_2 abatement cost. Another option is the normalization and weighting of separate indicators as well as of combined indicators to allow aggregating TEA and LCA results to a single indicator. This concept is formalized in MCDA. While LCA places MCDA in the interpretation phase, the integration activity includes MCDA in the impact calculation phase, as it returns a new result which is later interpreted.

Interpretation (IV). The interpretation ultimately prepares the decision under both economic and environmental aspects. Inter pretation is key to an integrated assessment, as it increases the understanding of the underlying trade offs and interactions be tween economic and environmental indicators. Therefore, inter pretation should encompass a detailed and transparent discussion of the collected or calculated indicators, concluded by a recom mendation. Furthermore, quality and consistency checks of the

Table 1
Descriptions of concepts used in this contribution: integration, alignment, combination, aggregation, composition.

Terminology	Description
Integrated assessment	*Integration* can be defined as the incorporation of elements as equals into a group (Merriam-Webster.com Dictionary, 2020a). TEA and LCA are separate elements with equal rank in the superordinate integrated assessment.
Alignment of scope/ inventory	*Alignment* can be defined as a specific arrangement of groups in relation to one another (Merriam-Webster.com Dictionary, 2020b). Alignment in the context of this contribution inherently refers to a high level of similarity of the information underlying each group. Aligned scope between TEA and LCA refers to the high similarity of system boundaries, selected allocation methods, geographical and temporal context. Aligned inventory refers to all data required in both TEA and LCA such as common material or energy balances from assessed process design.
Combined goal/indicator	*Combining* can be defined as individual entities becoming one number or expression (Merriam-Webster.com Dictionary, 2020c). Here, a combined goal refers to a single goal of one study with the purpose of integrating TEA and LCA results. A combined indicator is a new indicator formed by the division or multiplication of one environmental and one economic value (*e.g.*, carbon dioxide abatement cost [$/kg CO_2 eq abated], acidification per added value [kg SO_2 eq/$]) and can be characterized by its two-dimensional unit, the similarity to eco-efficiency (EE) indicators and the alternative term composite indicator
Aggregated indicator	*Aggregation* can be defined as many parts composed to a single body (Merriam-Webster.com Dictionary, 2020d).

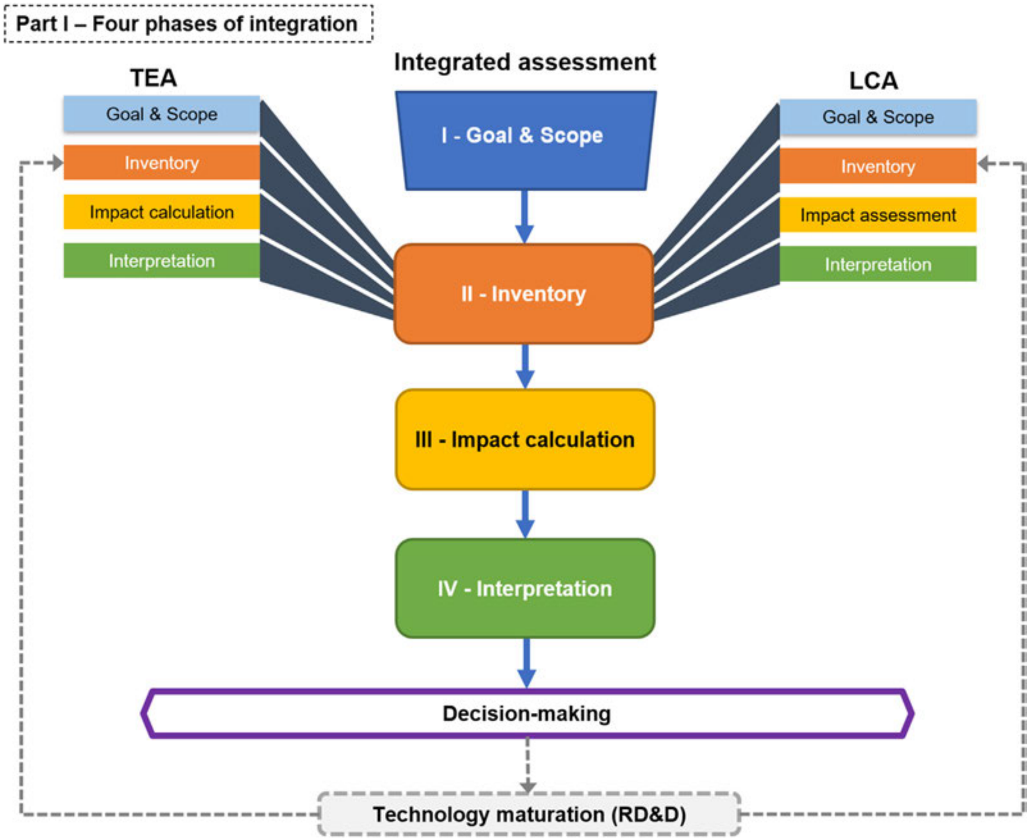

Fig. 2. Part I of the integration framework; integrated assessments consist of four phases (I-IV) with inventory phase (II) drawing data from subordinate TEA and LCA results; integrated assessments support decision-making that can lead to further technology maturation within research, development and deployment (RD&D); further iterations of TEA and LCA with subsequent integration can follow to support new decision-making problems.

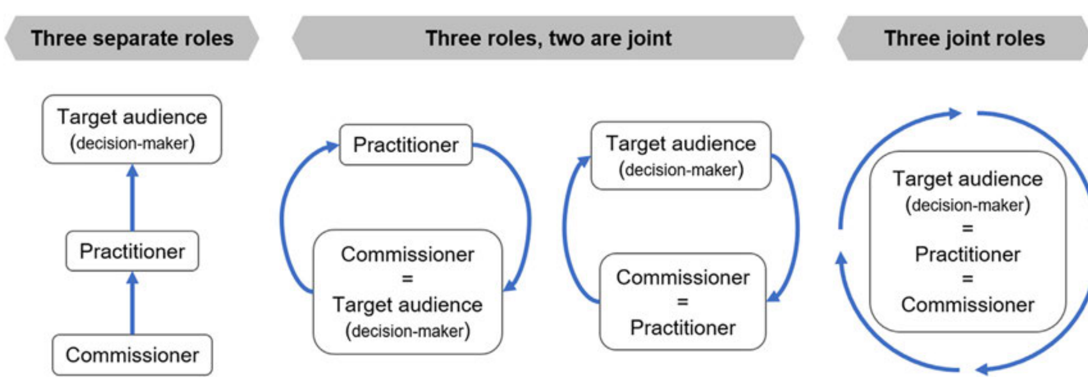

Fig. 3. The three roles in assessment (commissioner, practitioner, target audience) and their possible relationships.

integrated results, as well as uncertainty and sensitivity analyses, should be performed to illustrate the representativeness and reli ability of the discussed results.

3.3. *Part II — integration types*

The analysis revealed different approaches to combining TEA and LCA results. In some cases, a simple reporting of results without interpretation of how the two dimensions are linked is sufficient. In other cases, such linkages are specifically investigated in detailed discussions including numerically combining indicator results. Therefore, how should practitioners decide what type of integra tion is necessary to meet the objectives of the target audience regarding its decision making problem?

The framework distinguishes between two main categories of combined TEA and LCA: Reporting and Integration. ‘Integration’ studies are characterized by the superordinate assessment inten sively linking TEA and LCA results. Studies without such linking are considered as ‘Reporting’ of results. The ‘Reporting’ and ‘Integra tion’ categories can be further subdivided into types. This subdi vision does not imply any hierarchy, as the suitability of each integration type depends on the integration goal. The Reporting category consists of the types ‘separate reporting’ and ‘co report ing’. The Integration category consists of three types: qualitative discussion (‘Type A’), quantitative integration *via* combined indi cator (‘Type B’), quantitative integration including preferences

('Type C'). Each category and type have distinguishing characteristics and criteria with increasing specificity, as illustrated in Fig. 4.

There are two decisive differences between Reporting and Integration. First, for a study to be integrated, the data selected from each subordinate TEA and LCA must be sufficiently aligned according to what is stated by the goal (criterion 3, Fig. 4). However, this framework refrains from considering a full alignment in terms of identical system boundaries, assumptions, and technical inventory as mandatory for integration, as long as the required level of data alignment, according to what is expected by the goal of integration, is achieved. Second, the linkage of the TEA and LCA indicator results must be discussed and interpreted in detail (criterion 4, Fig. 4).

Separate reporting. This is the simplest type of combining TEA and LCA as it only requires that the subject of each assessment is sufficiently similar, meaning that the same process has been assessed – separate reporting must fulfill criterion 1 (Fig. 4). In separate reporting, the indicators are discussed separately but not compared or linked in a discussion. The decision maker is not provided with comparisons and conclusions. Separate reporting was not identified among the analyzed literature, as the search query did not allow finding reporting of single assessments in separate documents.

Co-reporting. In this type, TEA and LCA results are reported together, for example coinciding within the same document – co reporting must fulfill the criteria 1–2, (Fig. 4). However, the individual studies can be created independently. It is expected that the co reporting study would consist of separate discussions of environmental and economic indicators, optionally followed by only a very limited discussion (few sentences) linking economic and environmental results of any element of the system or the overall system.

Qualitative discussion-based integration (Type A). Here, a detailed discussion qualitatively compares economic and environmental results – Type A must fulfill the criteria 1–4 (Fig. 4). The discussion entails a link or relationship being made between LCA and TEA indicator results of certain system elements, such as identified hotspots, or of obtained Pareto curves depicting a multitude of scenario outcomes. The term 'qualitative' shall imply, that for the integration activity no additional numeric information is created, despite discussing quantitative results. Qualitative discussion can include the whole process, hotspots in sub processes and/or tradeoffs as required to achieve the integration goal. In this type of integration, the overall system boundaries of the separate TEA and LCA studies can differ, but those system elements selected for integration need to be suitably aligned in scope for the discussion to be meaningful.

Quantitative combined indicator-based integration (Type B). For Type B the key integration aspect is the calculation of a combined economic and environmental indicator, for example, cost of CO_2 abated – Type B must fulfill the criteria 1–5 (Fig. 4). The calculated combined indicator mathematically relates TEA and LCA *via* division of their indicator results. The term 'quantitative' refers to the numeric activity that achieves integration, not the use of quantitative data. As a numerical value is produced, the scope of the subordinate studies must be sufficiently aligned so that additional errors are limited. Type B integration is generally conducted for the whole process, not single system elements, allowing alternative processes to be compared.

Quantitative preference-based integration (Type C). For Type C the key integration aspect is the inclusion of the decision maker's preferences to prepare a concrete decision based on aggregating the subordinate TEA and LCA results, in other words weighting each criterion and summing them up into a new single value – Type C must fulfill the criteria 1–6 (Fig. 4). The quantitative (numeric) link in Type C is achieved *via* a multi criteria decision analysis (MCDA). With sufficient alignment of TEA and LCA, MCDA can be performed on the whole process or sub processes within the system elements identified as hotspots. MCDA can also include the use of combined indicators from Type B. It is outside the scope of this work to recommend specific MCDA methods, as the method chosen should be based on the specific goal and scope of each study. Guidance on

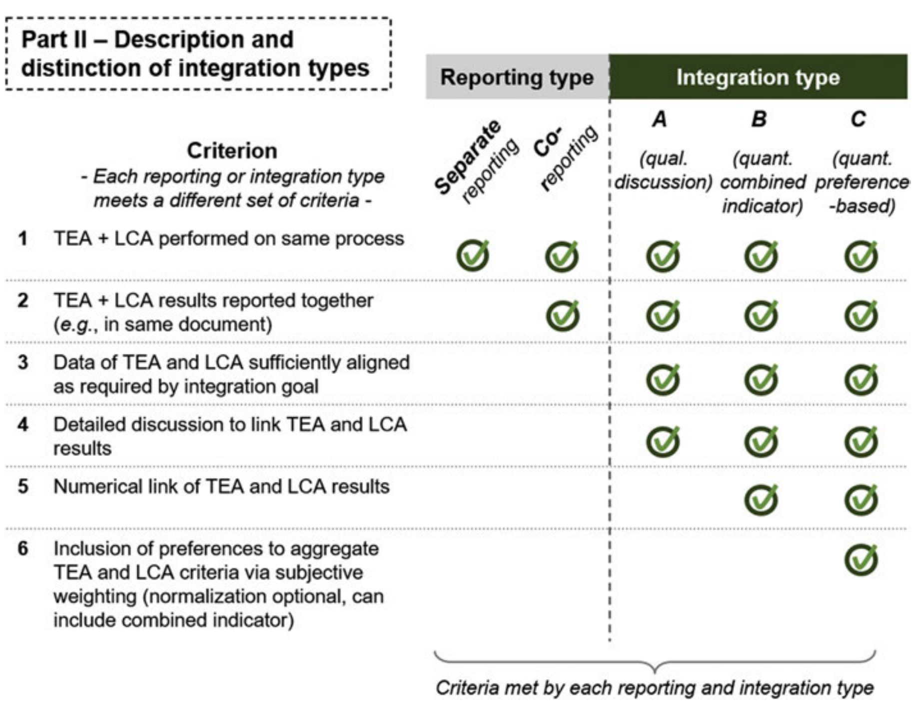

Fig. 4. **Part II** of the integration framework; Criteria matrix to distinguish between two reporting types and three TEA and LCA integration types (e.g., if only criteria 1 2 are met, then it is only co-reporting, not integration; if criteria 1 5 are met, then it is Type B integration); integrated assessments are required to meet at least criteria 1-4.

choosing MCDA methods can be found in literature (Guitouni and Martel, 1998; Jaini and Utyuzhnikov, 2017; Parnell et al., 2013; Serna et al., 2016; Steele et al., 2009; Wątróbski et al., 2019).

3.4. Part III – how to select the integration type

Whether it is necessary to conduct an integrated assessment instead of only reporting separate TEA and LCA results depends on the leading question of the target audience. If integration is required, the purpose of the assessment is to provide meaningful information that helps to solve this leading question. The selection of an integration type should be carried out as part of the integrated assessment's goal and scope phase. Considering there can be a variety of potential goals, the practitioner faces the decision which of the integration types A, B, or C is most suitable. Three criteria can be identified which govern the selection of the appropriate inte gration type and these can be approached as three steps (see Fig. 5):

1) The purpose of the integrated assessment,
2) Potential restrictions imposed by technology maturity (TRL),
3) Available resources.

Step 1) *Select the integration type according to the purpose of the assessment.* The first step for selecting an integration type is a clear definition of the purpose of the integrated assessment. Although practitioners are generally free to select any integration type for the identified purpose, the three Types are not equally recommended for all purposes. The list of purposes is not exhaus tive and different perspectives on integration are possible. It should be noted that integrated studies can have multiple purposes and therefore a mixture of integration types.

1 **Hotspot analysis.** Type A integration (qualitative discussion based) is recommended as hotspot analysis requires a dis cussion of the interlinkages between the parameters that are most influential. Here, integration should be limited to a qualitative discussion *via* Type A. A quantitative integration *via* Type B (combined indicator based) or Type C (prefer ence based) would create new numeric results. These would no longer visibly show the full information about the un derlying indicator results which are needed to enable deci sion making at the hotspot.
2 **Benchmarking.** Type B integration (combined indicator based) is recommended if the target audience is interested in a single criterion to compare a technology to its bench mark. The selected combined indicator is a relative, normalized value indicating the relationship of certain eco nomic to environmental impacts, thereby overcoming complexity and enabling quick interpretation across tech nology fields. Such indicators are valuable for future com parisons based on generally accepted indicators, such as carbon abatement cost.
3 **Selection of preferred option.** Type C integration (prefer ence based) is recommended when considering multiple indicators and process options. Multi criteria decision anal ysis (MCDA) is used for subjective weightings of criteria and aggregation of multiple indicator results. A single number will be returned that can be interpreted with a single indi cation, thus supporting the decision based on preferences. A prominent example is the preparation of a concrete invest ment decision for the deployment of a technology.
4 **Simplification of complex results.** Type C integration (preference based) is recommended if a reduced and easy to grasp information basis is desired for decision making. Type C integration facilitates this by applying MCDA for subjective weighting and aggregation of various criteria and results to a single number. In addition, Type A (qualitative discussion based) and Type B (combined indicator based) are optional for integration in this case, if the integrated assessment can be limited to one criterion or few criteria to also achieve the desired simplification.
5 **Presentation of non-reduced results.** Type B integration (combined indicator based) is recommended for a simplified presentation of results while keeping information about the original indicator units (non reduced). This purpose is often found in academic publications or studies with a diverse target audience. As combined indicators are innately relative results, the presentation of intermediate results to show absolute values is often desired in addition. In this case, Type A integration (qualitative discussion) is optional to present results in their original form as non reduced depiction, for example graphically via Pareto curves.
6 **Distinction between stakeholder perceptions.** Type C integration (preference based, MCDA) is recommended if the purpose of the assessment is to distinguish the views of different stakeholders towards a technology. By repeating the MCDA process with different sets of preferences, for example of different stakeholders, the effect of different weighting schemes on the indicated decision can be analyzed.
7 **Analysis of trade-offs.** Type A integration (qualitative discussion based) is recommended if the task in technology development is to choose from a set of technical options that each can have a different contribution to environmental and economic impacts. Integration should be limited to the qualitative discussion of absolute indicator results, option ally entailing the plot of a Pareto curve, to first understand what trade off between LCA and TEA criteria is caused by each option. The integrated assessment of trade offs can prepare process optimization which is part of further tech nology development.
8 **Early screening.** Type A integration (qualitative discussion based) is recommended for integration based screening of multiple technologies at lower technology maturity (TRLs < 4). Type A integration encompasses the collection of nominal information associated with economic and environmental criteria, completed by a qualitative discussion to link the results of TEA and LCA.
9 **Detailed screening.** Type B integration (combined indicator based) is recommended for integration based screening at mid and higher technology maturity (TRLs > 3). The calcu lation of a combined indicator is generally based on the systematic collection of numerical data which is required for detailed screening of technology options if no ranking based on preferences is intended.
10 **Ranking.** Type C integration (preference based, MCDA) is recommended to rank alternative scenarios. Generally, the alternatives will be ranked by their ability to reach a targeted goal. If this goal entails multiple criteria, then the MCDA process requires the conversion of TEA and LCA results by normalization and weighting. A screening of the selected alternatives can serve as a prior step to identify the under lying information for the MCDA.

Step 2) *Restrictions imposed by technology maturity (TRL).* In

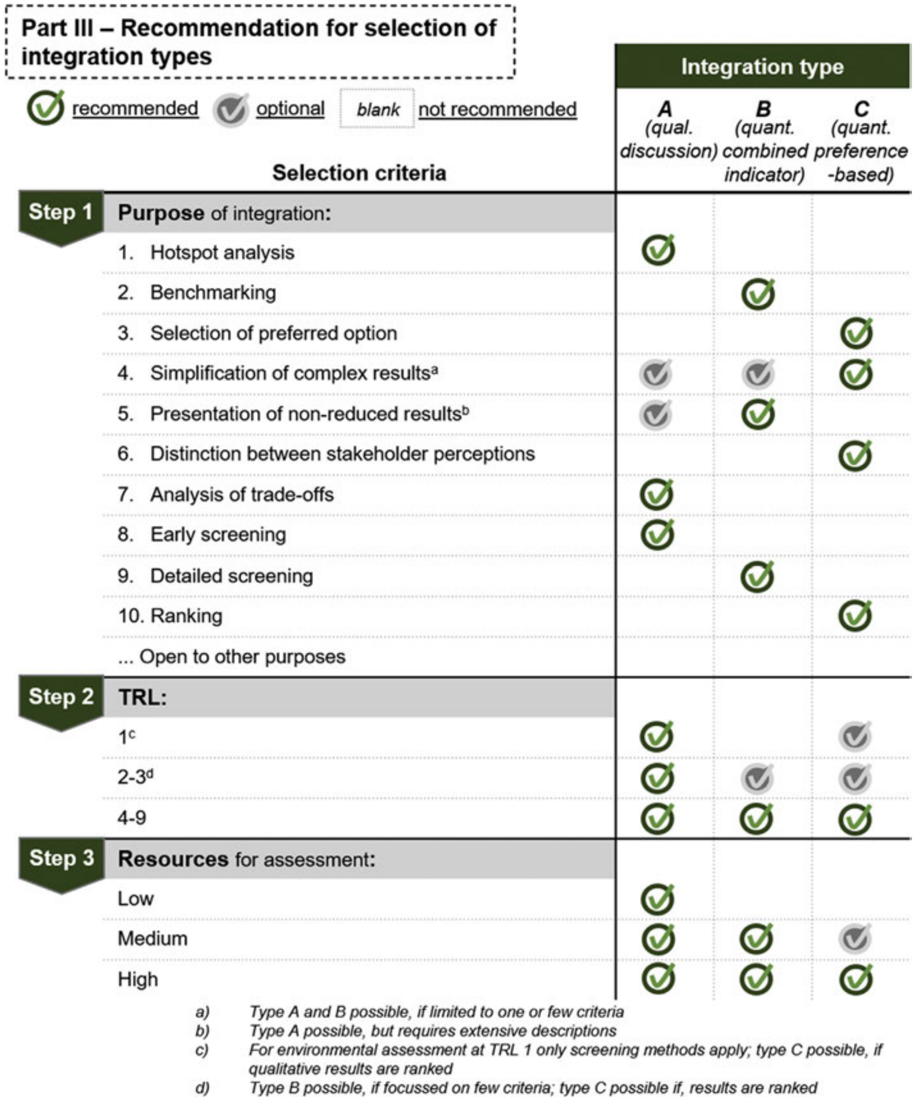

Fig. 5. Part III of the integration framework; Three-step approach to select a suitable integration type (A, B, C) according to the purpose of the assessment, TRL and resources for the assessment; marks indicate which type is recommended.

general, the higher the TRL, the more data are available and the uncertainty of assessments and integration decreases. For the assessment, the ‘observed’ TRL that reflects the data that are input into the assessment is relevant and decided on by the practitioner in the goal and scope phase. It can be lower than or equal to the ‘real’ TRL that reflects an unrestricted view on the current maturity of the technology.

TRL 1. Type A integration (qualitative discussion based) is recommended at TRL 1. By definition, no numerical data are available as the technology innovation only consists of an idea. For environmental assessment, this excludes LCA as a quantitative tool. Nevertheless, environmental screening methods can be applied. TEA at TRL 1 is also limited to a similar qualitative evaluation, therefore integration at TRL 1 is often limited to Type A with qualitative discussions. However, a simple form of Type C integration (preference based, MCDA) is applicable at TRL 1. Here, the purpose is limited to a (quantitative) ranking of alternatives based on qualitative information, for example when key aspects of the alternative ideas are evaluated by a red green color scheme.

TRL 2–3. Type A integration (qualitative discussion based) is recommended at TRL 2–3 as the discussion of a selected set of TEA and LCA indicators without further transformation is most suitable for the low data availability. Type B integration (combined indicator based) is optional at TRLs 2–3, as a combined indicator is based on a further transformation of already limited information. Generally, Type B integration should be limited to very few criteria with the least uncertain data. Type C integration (preference based, MCDA) is optional, as MCDA typically requires substantial information on numerous criteria and imminently loses information in the calculation and aggregation. High uncertainty of data can blur the MCDA result therefore, great care should be taken in the research stages of product development.

TRL 4–9. All integration types are equally recommended in the development and deployment stages (TRLs 4–9). The data availability is sufficiently high for each type and the choice mainly depends on the assessment purpose or resource limitations.

Step 3) *Restrictions imposed by resources.* Resources for an integrated assessment such as money, time, expertise or brain power need to be spent wisely to ensure that the uncertainty requirement of the integration stated in the goal and scope phase can be met. If it is found that the level of resources available does not match the types selected in Steps 1 & 2, goals and resources should be reviewed to ascertain which can be altered to achieve the outcomes required for decision making.

Low resources. Type A (qualitative discussion based) is recommended where resources are limited, as only indicators of TEA and LCA need to be selected and discussed, thereby reducing any additional effort of quantitatively linking these indicators.

Medium resources. Type A and the numerical evaluations proposed in Type B (combined indicator based) are recommended for a medium set of resources. Type C (preference based) is optional as MCDA usually necessitates a higher level of resources.

High resources. All integration types are recommended. Type C integration with MCDA often requires a long process of feedback cycles and reflection to determine an appropriate weighting scheme and is therefore recommended if a high level of resources is available or if a considerable effort is willing to be made.

4. Demonstration and discussion

4.1. Demonstration of type selection

To demonstrate the application of the framework it is applied to three generic scenarios that describe exemplary and fictitious practitioners investigating the production of methanol from CO_2 (see Fig. 6). The practitioners need to decide on a suitable integration type for their individual integration purpose, including the consideration of technology maturity and available resources. The examples illustrate how practitioners can derive the recommended integration type based on which criteria of the integration framework are met.

Type A Example In the first example, an academic researcher is looking to assess a laboratory based photocatalytic process to produce methanol (TRL 2–3). The researchers' goal is to identify economic and environmental hotspots within the process to enhance experimental development. Hence, the researcher structures both TEA and LCA studies to elucidate sub processes and specific inputs. In the example, a contribution analysis with respect to selected indicators is applied to compare the impacts of alternative photocatalysts. Here, the discussion of the hotspots could conclude, that further research should be concentrated on alternative 1 instead of alternative 2 due to similar contribution to cost at lower environmental impacts (e.g. lower levels of resource depletion). Thus, the purpose of the integration of both studies is to enhance the subsequent experimental design. The required decisions draw on an increased understanding of how the identified hotspots are linked in terms of resulting tradeoffs between TEA and LCA indicators. In this case, it is sufficient to discuss how the (quantitative) TEA and LCA indicators are interdependent and to allow a recommendation for decision making. The nature of integration may remain qualitative (Type A), as only existing indicators need to be described. In contrast, the creation of combined indicators or a weighted aggregation of results is not needed. To support the qualitative discussion graphically, the researcher could construct Pareto curves depicting the TEA and LCA indicator results of the alternatives. Although the low TRL and limited resource availability indicate both Type A or B integration, type A with qualitative discussion will provide enough information for the researcher to answer the leading question, without over complication or increased uncertainty due to new information.

Type C Example In the second example, a technology manager in a company wishes to select the optimal technical design parameters for a demonstration plant producing methanol from CO_2 via a thermocatalytic route with H_2 produced by water electrolysis. Data are based on pilot plant trials and three alternative process simulations (TRL 6) differing in the selected electrolysis technology (alkaline, proton exchange membrane or solid oxide electrolysis). This indicates that the data reliability and availability will be good, therefore reducing uncertainty for Type B or Type C integration. As resources are not an issue, all three integration types could be applied. Therefore, the choice of integration type will be primarily based on the purpose of the study. Here, the practitioner is tasked to prepare the information basis for a concrete decision by including multiple economic and environmental indicator results. The concrete decision shall be prepared by ranking the three alternative options according to the decision maker's preferences. While the qualitative discussion of the linkage between the indicator results is certainly required for the interpretation of the derived conclusions, the integration approach needs to aggregate these results into a single value, thereby providing additional information. Therefore, MCDA instruments can be applied to identify the optimal system, indicating preference based integration (Type C).

Type B Example In the third example, a policy advisor is looking to compare viable routes to produce fossil free low GHG emission methanol for the chemical industry. This indicates the purpose is benchmarking options against each other. The processes to be assessed range in maturities from TRLs 3–8, and only routes that exhibit the potential of lower greenhouse gas emissions compared to the fossil based route are of interest. It is the goal to identify the route with the biggest economic lever to reduce environmental impacts. A simple, preferably non subjective instrument is required to communicate the benchmark results to a diverse target audience. Here, benchmarking suggests a Type B integration (combined indicator), as it results in a single criterion combining economic and environmental criteria without entailing weighting schemes. The policy advisor could conclude that the cost of carbon abated is a suitable combined indicator to compare the routes. Furthermore, data and resource availability indicate that Type C may not be appropriate as limitations on both data and resources are present. Therefore, the overall recommendation is Type B integration (combined indicator).

4.2. Discussion of framework

The focus of the proposed framework is on the integrated assessment of chemical technologies in development. This decision was made for three reasons: 1) the transition towards green chemistry requires a continuous assessment of the developed innovations, 2) TEA and LCA approaches for this field show a similar enough structure for alignment and integration, and 3) this field experiences a lack of guidance for integrating assessments. It is also acknowledged that the framework could be adapted for other technology fields and to include further assessment types (for example, social acceptance assessment).

In **Part I**, the definition of the multi layer assessment approach places integration as a superordinate assessment over subordinate TEA and LCA. This has not been formulated as such before in the related literature. Integration is here defined as a distinct assessment with four phases: goal and scope (I), inventory (II), impact calculation (III), interpretation (IV). Therefore, a targeted and transparent discussion of critical integration aspects along the assessment phases is possible.

An adequate definition of the integration goal is found to be lacking in most studies of the literature analysis. Accordingly, the framework emphasizes the importance of understanding clearly the purpose of the integrated assessment which is key to selecting

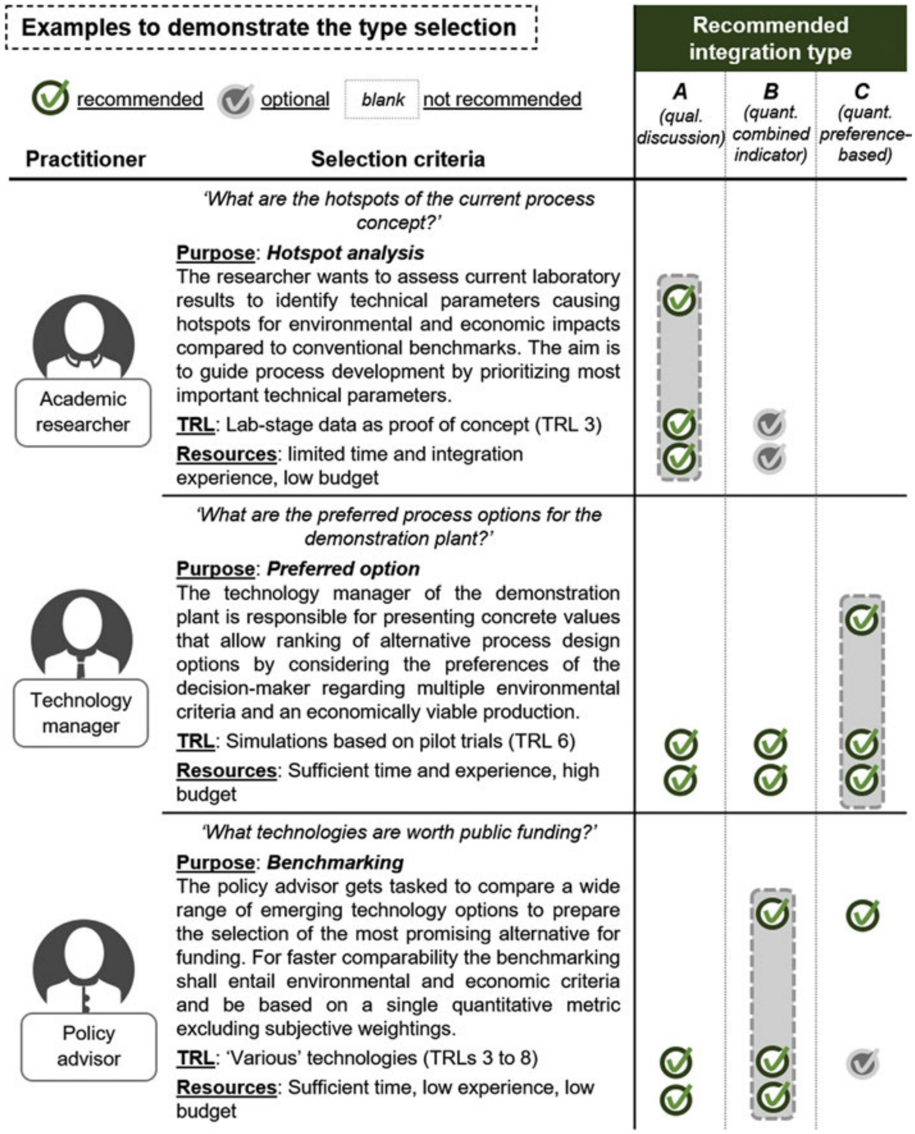

Fig. 6. Selection of a suitable integration type demonstrated by three exemplified integration practitioners.

an appropriate integration type. A statement of generic goals such as 'to identify economic and environmental impacts' does not sufficiently reflect the purpose. Therefore, the framework guides the practitioner to include meaningful purposes in the goal, such as 'to analyze the hotspots in the process for further optimization by engineers' or 'to enable policy makers to identify processes with the cheapest carbon abatement cost'. This guided goal setting enables subsequent methodological choices.

The inventory of an integrated assessment is fed by indicator results of the subordinate TEA and LCA. Hence, an understanding of the similarities and differences of TEA and LCA principles is critical. This can be achieved by taking a closer look at how both assessments are performed along their similar four phases (I IV), as will be done in the following:

- Goal and scope (phase I) of TEA and LCA serve the same general purpose so that similar principles guide the distinct methodological choices. However, the selection of benchmarks for comparison within each assessment can be driven by deviating perspectives, resulting in deviating assumptions for the underlying data. An example would be the selection of the most economic benchmark in TEA which might not be the most environmentally friendly, as would be required for the LCA benchmark. Thus, if the integrated assessment discusses the performance of the technology, the benchmarks need to be identical.
- The inventory (phase II) of TEA differs from LCA inventory in three major aspects: i) there is no single, unambiguous correlation of physical flows with monetary flows; ii) the correlation can be non linear, for example, material costs do not need to linearly increase with an increased material flow, as would be the assumption for environmental impacts; iii) conceptual flows with no physical representation can have monetary impacts, such as taxes, purchase price premiums or customer demand fluctuation affecting the selling price. Accordingly, this inherent difference in data formation and composition should be paid attention to when identifying any potential bearings on the uncertainty of the integrated TEA and LCA results.
- The impact calculation (phase III) in TEA and LCA shows methodological differences posing additional challenges for interpreting integrated results. The units of indicators are different and prevent a simple aggregation of results. TEA often considers

dynamic indicators to include time preference, whereas LCA impacts are often considered static.
- The interpretation (phase IV) in TEA and LCA again follows a similar generic approach, although decision makers reading an integrated assessment need to be aware of the underlying rea sons for uncertainty, for example, if data are more reliant on market dynamics than on physical flows.

Part II of the framework introduces three newly defined inte gration types (A, B, C), which are the basis for the phases of impact calculation (III) and interpretation (IV). These type definitions were tested to validate their fit with existing integrated studies. Firstly, the types were determined for the analyzed set of 70 papers, then further validation was carried out against a sample for a specific technology field. The field of CO_2 utilization technologies (Styring et al., 2015) was chosen, as integration of LCA and TEA has been highlighted as a desirable assessment tool for this area (Mission Innovation, 2017; Müller et al., 2020; Sick et al., 2019; Zimmermann et al., 2020a, 2020b). From the non reduced litera ture set of 711 papers, 25 papers met the required criteria of con taining both an economic and environmental assessment and covering CO_2 utilization (a summary of the results is found in the Electronic Supporting Information). Therefore, considering both sets together a total of 95 papers were analyzed. The distribution across the integration and reporting types is presented in Fig. 7. No papers were found that could not be fitted to one of the types. However, the type 'separate reporting' is not included, as all papers were screened to include both an economic and environmental assessment. In both literature sets, co reporting and Type C inte gration (preference based) are most prevalent. However, in the smaller set of CO_2 utilization literature, a fairly uniform distribution of reporting and integration types is observed.

Part II of the framework further presents a criteria matrix (see Fig. 4) to distinguish the reporting and integration types. These criteria can be applied in a straightforward fashion. An exception is criterion 3 that demands sufficient alignment of TEA and LCA data in accordance with the integration goal. While TEA and LCA results contribute inherent uncertainty to the final integration result, additional integration uncertainty is correlated inversely with the alignment of TEA and LCA data, as depicted in Fig. 8. In general, a higher degree of alignment lowers additional uncertainty. The highest level of uncertainty is theoretically introduced when TEA and LCA would rely on entirely different data; the lowest level of uncertainty follows from TEA and LCA that rely on the same data wherever possible. Criterion 3 can only be met if the level of alignment reflects the accepted uncertainty of integration defined by the goal and scope. In contrast, some proposed frameworks in literature demand full alignment as the leading criterion to be met for assessments to be integrated (Azapagic et al., 2006; Miah et al., 2017; Serna et al., 2016; Thomassen et al., 2019). In those cases, the specified set of data would need to be common for both TEA and LCA. The methodology described here does not require a full or a pre determined degree of alignment of TEA and LCA data for meaningful integration. An adequate degree of alignment follows the integration goal: the degree of alignment needs to be such that the uncertainty obtained in the final, integrated result is in line with the uncertainty requirement implied in the integration goal. Therefore, the framework is flexible enough to apply to any goal that is set; and does not cater to a specific level of uncertainty that is pre determined by the way the integration is performed (*i.e.*, fixing which data basis have to be common for both TEA and LCA).

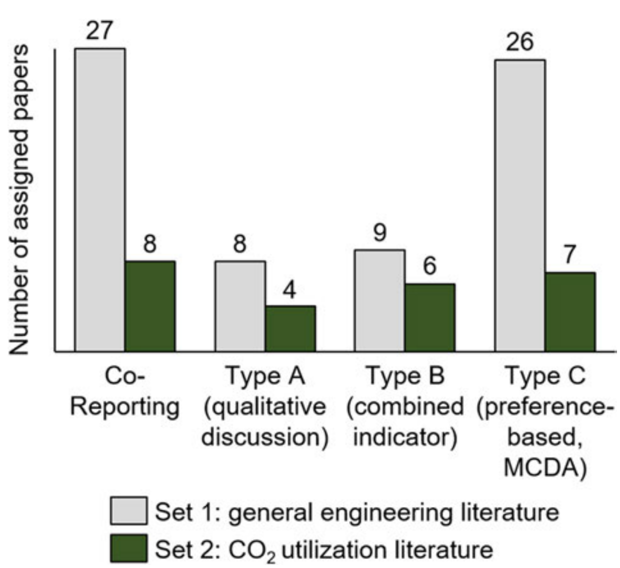

Fig. 7. Distribution of identified reporting and integration types across two sets of analyzed literature; Set 1 is the sample of 70 randomly selected studies from a non-reduced set of 711 papers, Set 2 is the field-specific validation set containing all 25 studies within the non-reduced set of 711 papers matching the concept of CO_2 utilization.

Part III of the framework proposes the three step procedure to select a suitable integration type which is designed in a way that other purposes can easily be added. We hereby acknowledge that the specific environments, tasks, and circumstances that practi tioners find themselves in can vary substantially. To make sure the framework can be applied right away by practitioners without substantial prior experience, the proposed restrictions set by technology maturity (TRL) and resources are kept at a low level of granularity. However, advanced practitioners may benefit from expanding the framework by including a finer differentiation of the nine TRLs for data availability or additional categories allowing finer sorting of the level of resources.

Overall, the specificity of the proposed framework seeks to provide a balanced level that is, on the one hand, detailed enough to give strong guidance, and on the other hand, open and flexible enough to serve stakeholders with different backgrounds regarding experience, skill, function, and mission. No suggestion for concrete indicators is included and no normalization references or weight ing schemes for MCDA are proposed. Whilst such specification could facilitate the comparison of different integrated assessments, it is necessary to leave this level of specification to the practitioner: due to the unique goal and scope of each integrated assessment, appropriate choices for one may not be appropriate for another. Practitioners should choose methodological options such as selected (combined) indicators, normalization, weightings, or MCDA methodologies, based on the advantages and disadvantages of each method with respect to the integration goal. Specifying a discrete range of such options would be detrimental to the flexi bility and applicability of the framework.

5. Conclusion

TEA and LCA have proven to be valuable tools for interpreting impacts separately in regard to different criteria, however, properly integrating them can effectively enhance decision making. The proposed integration framework increases the knowledge basis by providing a methodology that defines TEA and LCA as subordinate assessments linked by a superordinate integrated assessment. Inte gration can only support decision makers if it is understood as in dividual assessment providing additional insights linking the LCA and TEA reports. The framework provides practitioners with step by step guidance through the four phases of integration and can quickly be adopted due to its familiarity with LCA and TEA methodologies.

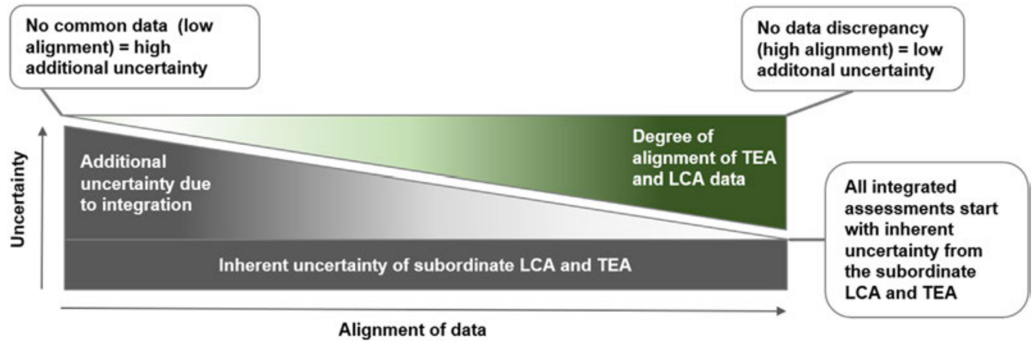

Fig. 8. Inverse relationship between the alignment of scope and data between TEA and LCA and acceptable additional uncertainty caused by integration.

Integration can only be achieved by interpreting the link be tween TEA and LCA as the main criterion, thus avoiding mere reporting of results. A one size fits all solution for integration would force practitioners to make an identical methodological choice for varying goals. Therefore, the framework derives three types of integration characterized by: the limitation to a qualitative discussion (Type A), the calculation of combined indicators (Type B) or the inclusion of preferences *via* multi criteria decision analysis (Type C). Here, practitioners are guided by the presented step by step approach for choosing a suitable integration type. It allows for type selection according to the intended integration purpose as well as restrictions imposed by technology maturity and resource availability. By developing a widely adopted understanding of in tegrated assessments, it can be ensured that decisions will no longer be based on either an economic or an environmental crite rion in isolation, but on highlighting their interlinkages. Further more, in the future, the framework could be expanded to include social sustainability metrics by incorporating assessments such as SLCA. However, if SLCA results are of qualitative nature, then combined indicator based integration (Type B) would not be supported.

This framework helps to expedite advances in sustainable chemical technology development, as it provides a consistent un derstanding of integration to assist diverse stakeholders in select ing a suitable integration methodology.

CRediT authorship contribution statement

Johannes Wunderlich: Conceptualization, Methodology, Investigation, Data curation, Writing original draft, Writing re view & editing, Visualization, Project administration. **Katy Armstrong:** Conceptualization, Methodology, Investigation, Data curation, Writing original draft, Writing review & editing. **Georg A. Buchner:** Conceptualization, Methodology, Writing original draft. **Peter Styring:** Supervision. **Reinhard Schomacker:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125021.

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7 Developing a Triple Helix Approach for CO_2 Utilisation Assessment

This chapter comprises of a reprint of a research paper by McCord, Armstrong and Styring, (2021). The supplementary information for the paper can be found in the Supplementary Material section at the end of the thesis. There is a joint 50:50 contribution to the work between McCord and Armstrong for conceptualization, methodology, formal analysis, investigation, data curation, visualisation, and writing; Styring provide supervision, review and editing of the work.

This chapter explores the concept that assessment of the sustainable impacts of CO_2 utilisation technologies needs to expand beyond environmental assessment through life cycle analysis (LCA) and techno-economic analysis (TEA). Social impact assessment (SIA) should also be considered to ensure no inadvertent harm to humans is caused by CO_2 utilisation deployment. This paper explores the subject of assessing social impacts noting that these are different from social acceptance (see chapters 9 and 10). A methodology for screening potential social impacts for emerging CO_2 utilisation technologies is presented and demonstrated to determine potential hotspots to be address. This work is the first to explore the application of social impact assessment in CO_2 utilisation. The proposed triple helix approach encompasses LCA, TEA and SIA enabling trade-offs between environmental, economic and social impacts to be explored. This triple helix enhances effective decision making for understanding the potential of development and deployment of CO_2 utilisation technologies.

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Developing a triple helix approach for CO_2 utilisation assessment†

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Assessment of the sustainability of CO_2 utilisation technologies should encompass economic, environmental and social aspects. Though guidelines for economic and environmental assessment of CO_2 utilisation (CDU) have been presented, a methodology for social assessment of CDU has not. Herewith, social impact assessment for CDU is systematically investigated, a methodological framework derived and examples of application given. Both process and deployment scenarios are found to be key factors in the assessment and the sourcing of raw material is observed to be a hotspot for social impacts within the assessed CDU technologies. This framework contributes a new aspect to the development of holistic sustainability assessment methodologies for CDU by enabling a triple helix to be created between life cycle assessment (LCA), techno-economic assessment (TEA) and social impact assessment (SIA). Therefore, the triple helix approach will enable trade-offs between environmental, economic and social impacts to be explored, ultimately enhancing effective decision making for CDU development and deployment.

Introduction

Sustainability is key to the future of green chemistry and holistic methodologies to assess this are a necessity.[1] Sustainability should be considered as a three-dimensional concept, with the constituent parameters generally defined as the economy, society and the environment. Life cycle assessment (LCA), life cycle costing (LCC) or techno-economic assessment (TEA) and social impact assessment (SIA) or social life cycle assessment (SLCA or S-LCA) are common methodologies used to assess the three dimensions. These concepts can be further considered as a triple helix structure with cross-linkages between parameters. By expanding our thinking to consider the whole life cycle of a product (life cycle thinking) within the facets of environment, social and economic impacts we can seek to reduce resource use, emissions, social and environmental impacts.[2] Of

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these three assessment methods, SIA or S-LCA has historically been the least developed.[3,4]

Within the field of carbon dioxide utilisation, most technology assessments to date focus primarily on assessing the economic and environmental impacts of emerging carbon dioxide utilisation (CDU) technologies and their enabling infrastructure.[5] Increasingly, these studies are moving towards being "integrated" with the intention of investigating trade-offs between environmental benefits and increased financial burdens.[6] This shift into a two-dimensional assessment approach is one which should be encouraged but leaves open the risk that the third societal pillar remains neglected. Therefore, approaches to integrate all three aspects are required to attain truly sustainable CDU technology deployment.[6–8] Guidelines for the economic and environmental assessment of CDU have recently been published to steer practitioners through methodological choices in CDU assessment.[9] However, such guidelines or methodologies do not exist for CDU social assessment, therefore the triple helix cannot easily be completed.

Social impacts should not be confused with social acceptance. Social acceptance is a measure of which an innovation will be accepted or rejected by key actors whereas social impacts measure the consequences of actions on society. Of course, there is an interlinkage between these aspects as social impacts can have an effect on social acceptance. Social acceptance covers the dimensions of socio-political acceptance, community acceptance and market acceptance.[10] Some explorations into the social acceptance of CDU technologies have been investigated,[11–15] though research in this area is still sparse. Generally, CDU technologies are perceived in a positive manner though with some hesitation.

Social impact assessment (SIA) analyses the intended or unintended consequences to humans of new actions. SIA can assist in the development of new chemical technologies, yet such assessment has not been readily applied to CDU. Typically, social impact is considered at a later stage of the development cycle, predominantly in deployment and the full impact may not be realised for many years afterwards. However, leaving such considerations until high technology readiness (TRL) could lead to inadvertent investment in socially unsustainable CDU processes. Therefore, questions are raised as to how SIA can be applied earlier and whether earlier application gives meaningful assessment results? Furthermore, due to the linkages between CDU, renewable energy deployment and industrial symbiosis opportunities, can the indirect impacts (such as using conflict minerals in catalyst synthesis) also be addressed?

Methods of social impact assessment

Social impact assessment is defined by Becker[16] as "the process of identifying the future consequences of current or proposed actions, which are related to individuals, organisations and social macro-systems". Therefore, the focus of social impacts should be on the corporate social responsibility of the activities undertaken by the company which will affect current and future generations.[17] As such, many organisations report social impacts using such mechanisms as the Global Reporting Initiative (GRI)[18] or the UN Sustainable Development Goals (SDGs),[19] however these tend to report on ongoing deployed activities or products rather than emerging technology opportunities. Kühnen *et al.*[20] identified five main frameworks used in social performance measurement research: GRI sustainability reporting, UNEP and SETAC SLCA guidelines,[21] UN SDGs, SAI SA 8000 and ISO 26000. Of these, the most commonly used are the GRI and UNEP & SETAC SLCA guidelines and most researchers, although assessing varying industry sectors and products, tend to use similar SLCA subcategories.

The ‘International Principles for Social Impact Assessment’[22] recognises that a definitive definition of guidelines for SIA is complex and that guidelines need to be evolved from core values and principles. All issues that affect people indirectly or directly are relevant in SIA, but guidelines for assessment can enhance practice and are therefore beneficial. To tackle this gap, the UN Environmental Program (UNEP) with the Society of Environmental Toxicology and Chemistry (SETAC) published guidelines for stakeholders for the assessment of social impacts of products in 2009.[23] The guidelines aim to be used as a skeleton approach to enable practitioners to identify key elements which should be considered in a study. The guidelines and methodological sheets[21,24] identify five stakeholder categories: local community, value chain actors, consumers, workers, society. Each of these stakeholder categories is then broken down into subcategories with examples of inventory indicators and data sources to assess the category being given (Fig. 1). The practitioner can then determine appropriate indicators within the subcategories for the scope of their assessment. These guidelines have been widely used and form the basis for many S-LCA studies.[25–29]

The European Commission Joint Research Centre conducted a state of the art review of SLCA, concluding that methodological development and harmonization is still in a preliminary stage when compared to LCA.[30] The JRC highlights the role that S-LCA can play in supporting decision making by identification of hotspots, but also recognises the S-LCA, TEA and LCA can result in conflicting indicators, for example, high wages are seen as positive in S-LCA but have a negative impact in TEA. Issues surrounding data availability, quality and reliability are also highlighted.

Indicators for S-LCA can either be qualitative, semi-quantitative or quantitative in nature.[4,31] Quantitative indicators use statistical sources and can be based on scoring methods. Qualitative indicators can be more exploratory and descriptive in nature and can be used to highlight potential problems. Popovic *et al.*[32] suggested 31 quantitative indicators which can be used to assess supply chains. Particularly focusing on labour practices and human rights the indicators cover

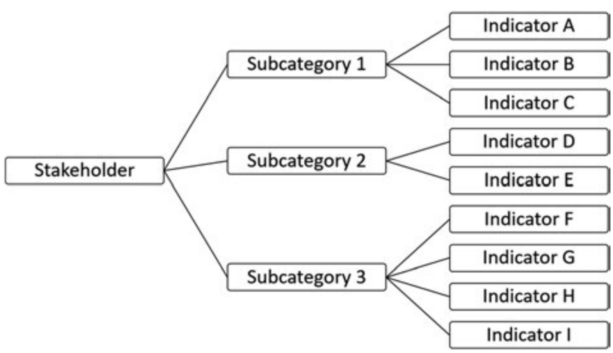

Fig. 1 Structure of UNEP/SETAC guidelines. Adapted from ref. [21].

issues found in company sustainability reports and can be used to monitor the supply chain.

Social impacts for the chemical and process industries are often considered within a broader sustainability assessment incorporating economic, environmental and social aspects. Markeviius *et al.*[33] identified 35 sustainability criteria often found in literature, of which 15 related to social dimensions, 4 to economic and 16 to the environment. 46 experts were asked to rank the criteria for relevance, practicality, reliability and importance and it was found that social criteria ranked lowest in the four attributes. Husgafvel *et al.*[34] created a sustainability index which incorporates both impacts within the supply chain and plant operations, however this is based on deployed technologies and hence depends on organisational data. Haaster *et al.*[35] developed a framework for S-SLCA of novel technologies covering four categories of concern (autonomy; safety, security and tranquility; equality; participation and influence) and 11 mixed qualitative and quantitative indicators to assess these categories. Here the quantitative indicators are aggregated to give a final score (weighted or unweighted), whilst qualitative indicators are used to identify potential concerns. Sector specific sustainability indicators have also been derived (often from frameworks such as GRI or UNEP/SETAC) for example for the mining and minerals sector.[36,37]

Social impact assessment in CO_2 utilisation and emerging technologies

Zimmermann *et al.*[5] highlights the lack of social impact assessment in emerging technologies. The review states that only five social indicators were identified as being employed in social assessment in CDU. Zimmermann found that no CDU studies incorporated assessment of technical, economic, environmental and social impacts, and that CDU social assessment was lacking across all TRLs. Pieri *et al.*[38] reviewed holistic assessment for CDU value chains, in the modelling approaches identified, none employed social impact assessment. Pieri *et al.* concludes that social impact assessment has been ignored and a more holistic approach to assessing sustainability is needed.

The low technology readiness (TRL) of many CDU processes has been identified as an issue for data gathering for social assessment.[39] However, as CDU processes have the potential to provide sustainable solutions in numerous sectors, the low TRL should not inhibit attempts to establish how social impacts could affect CDU deployment. Rafiaani *et al.* highlights that the lack of data can be tackled using experts to identify the most relevant areas to focus social assessment on.[39] Basing the approach upon the UNEP/SETAC guidelines, Rafiaani *et al.* indicates that the main stakeholders for CDU are workers, local community and consumers and therefore only assess in these areas. CDU experts were then asked to rank the importance of the UNEP/SETAC indicators for a stakeholder group. The experts highlighted 'end of life responsibility' and 'transparency' for the consumers, 'fair salary' and 'health and safety' for workers and 'safe and healthy living conditions' for local community as the most important indicators. However, the work did not apply the assessment to any CDU technology to determine if there are significant differences in these areas between the CDU technology and the current technology it would replace. Chauvy *et al.*[40] incorporates some aspects of SIA into the assessment of emerging CDU products by assessing health and safety aspects. In discussing multi-criteria decision analysis (MCDA) approaches for selecting CDU products it was recognised that social aspects were often mixed with environmental criteria but should be assessed separately.[41] Sacramento-Rivero *et al.*[42] considers an approach to sustainability assessment for processes in the conceptual design stage. However, only the aspects of employment and community development are investigated as social impacts and therefore many social considerations are ignored.

Research question

This work focuses on SIA for CDU technologies. Whilst a number of CDU technologies have reached commercial deployment, the vast majority remain under development at varying levels of maturity. Currently, there is little guidance available on the application of SIA for the specific scope of CDU technology development and deployment. To ensure CDU technologies are truly sustainable, herewith the application of SIA to CDU technologies is investigated through the development of a tailored assessment framework. This framework is then applied to a number of CDU technologies and deployment scenarios to illustrate its potential utilisation and highlight any limitations regarding practical implementation and feasibility of the suggested indicators.

This research aims to clarify:

• Which social indicators are key when assessing CDU technologies in a screening-type assessment and should therefore form the baseline of any assessment?

• How should these indicators be assessed – qualitatively or quantitatively?

• How social impacts are distributed between the CDU technology and the deployment scenario?

Methodological development and general principles

Indicator development

The UNEP/SETAC S-SLCA guidelines provide a comprehensive skeleton framework for the development of SIA for products identifying stakeholder groups and key subcategories for the assessment. Therefore, the framework is utilised as a starting point for adaptation to develop SIA for CDU. As discussed, most CDU processes are considered as low maturity or emerging technologies and thus the focus of this work is to develop a SIA framework suitable for assessing technologies at this stage of the development cycle. However, although CDU technologies themselves are classed as emerging, many aspects of their supply chains are fully or highly developed, therefore even with low TRL inventory data for the CDU technology insights into possible social impacts can be obtained or estimated. Given the available data and the uncertainties surrounding both technologies and impact assessments of these at this stage, a 'screening type' assessment was developed – primarily focussing on the identification of potential hotspots, risks and 'red flags' within both the supply chain and the process itself. The developed SIA can be aligned with TEA and LCA studies with a similar scope, adding a third dimension for stakeholders to consider in their process & scenario analysis. Given this intention, the indicators and data used to estimate them remain fuzzy and partially dependent on the practitioner's judgement based on the available data. Sourcing data is a known issue in impact assessment in general, thus the presented framework will focus on utilising open access data where possible to allow for a wider range of decision makers/TEA & LCA practitioners to utilise the framework in their chosen decision analysis.

The UNEP guidelines outline a total of 30 assessment subcategories split between five stakeholder groups, however given the identified scope of this framework many of these were deemed unnecessary for inclusion. Removing subcategories from consideration also allows for a streamlining of data collection and assessment, creating a better fit with the intended utilisation of the framework. In most instances, subcategories were discarded if the UNEP description and assessment aim suggest that the impact is dominated by organizational decisions related to broader corporate behaviour rather than the specific selection of a technology for development or deployment. The indicators used are designed to reflect data availability – users can amend these to fit their data and/or their assessment goals/technologies. This flexibility in the selection and application of indicators is aligned with the principles outlined in the UNEP S-LCA guidelines, where users are encouraged to determine which indicators best suit their assessment needs.

To determine whether a subcategory was needed, a two-dimensional assessment was made considering both:

- Importance of technology choice on the impact subcategory (high or low)
- Importance of indirect relationships on the impact subcategory (high or low)

Scoring each subcategory on both dimensions allows for the determination on how important its inclusion is for the selected scope. A subcategory in which the technology choice has only a low importance is unlikely to require assessment as other organisational behaviours and choices are more likely to be a driving factor. The second dimension of this assessment is more nuanced, but ultimately subcategories dominated by direct relationships rather than indirect ones are less likely to require assessment. Direct relationships are defined here as those that the organization are involved on a 'first party' basis, with indirect being all other subsequent relationships. Through direct relationships an organization can choose suppliers or vendors/customers that can be vetted for the mitigation of risks for negative social impacts associated with technology choices. Indirect relationships however may be more opaque, particularly if the supply chain for an input/output is extensive or complex in its nature. It is here where the organization may have less influence or ability to directly minimize its negative social impact and thus these factors are of more concern for assessment.

Serious efforts have been made to counteract unsustainable practices within supply chains, often with the intention of reducing the risk of utilising products that may impact societies or the environment negatively. Both compulsory (*e.g.* legislative) and voluntary (*e.g.* sustainable trade organisations) systems exist to address identified issues. However, the existence of such systems does not remove the need for assessing the social impact of an operation, even if it is assumed that these systems would be utilised where required. This effort to minimise negative social impacts should be seen as akin to optimising a process to minimize environmental impact or maximize profitability – an action that may be influenced by the results of an assessment but one that is independent of the assessment methodology itself. Furthermore, products that appear to meet voluntary or compulsory standards can still carry risk. As the proposed assessment is of a screening nature and for emerging technologies, the exact source of products and their supply chain will often be unknown. However, this does not negate the importance of including such indicators at this stage to 'flag' potential hotspots through considering already established supply chains. By flagging these hotspots early organisation choice in deployment or alteration of the process during development could mitigate any potential negative impact.

To illustrate this, two examples are explored: palm oil and gold. The Roundtable on Sustainable Palm Oil (RSPO) was created to 'develop and implement global standards for sustainable palm oil' and members include many of the world's biggest palm oil consumers. However, criticism persists both on the RSPO[43] and on the certifying of palm oil as sustainable when produced in areas where heavy deforestation and habitat destruction occurred less than 30 years ago.[44] Arguably more pressing are NGO reports on 'conflict' and 'illegal' palm oil[45,46] that state this palm oil is entering the supply chains of RSPO members. These illicit mills are shown to have significant negative impacts to both the environment and society, infringing the human rights of local communities in the process.

Illicit gold mining in Peru is known to cause significant negative impacts to local communities,[47] driven by criminal exploitation and organized crime. These impacts range from health (a reported 30 tons of mercury is dumped in rivers and lakes in the Amazon region every year, generating dangerously high levels of the material in the watercourse) to social issues such as the trafficking of women and young girls to mining towns to work in brothels. It is reported that in Delta 1, a mining settlement, alone there are approximately 2000 sex workers of which 60% are underage.[47] La Rinconada, another settlement, has an estimated 4500 girls trafficked for sexual exploitation to work in bars frequented by miners. The same report alleges that 35 tons of contraband gold were shipped *via* Lima to the USA and Switzerland between February and October of 2014 alone.

In 2018, Metalor, a Swiss gold refinery, stopped taking gold from the Peruvian Highlands region (including the aforementioned settlement of La Rinconada) that had been certified as 'sustainable' due to concerns of its origins. The company is quoted as stating that whilst they believed that operations were conducted 'in a proper way', they couldn't guarantee that this was the case 'due to the complexity of the supply chain'[48] – the company had processed an estimated 106 tonnes of gold from a Chilean company operating in the region, Minerales del Sur, since 2001 before halting purchases. Metalor customers at the time of the investigation included major technology companies demonstrating how feasible it is for illicit materials to enter the supply chains of companies.

Both of these examples highlight the need to consider in as much granularity as possible the indirect relationships involved in supply chains through SIA. In relation to CDU, awareness of how these issues could impact raw materials such as metal catalysts should be considered. Ultimately these examples illustrate that given the identified scope of this framework there is a need to include a focus on these indirect relationships that are particularly impacted by the choice of technology.

Table 1 shows an abridged version of the framework (showing only two stakeholder categories, the full version can be found in the ESI†) details the subcategories selected from the UNEP/SETAC guidelines identified for inclusion in the SIA framework for CDU. These categories were all determined to be of importance for the assessment scope, utilising the two-dimensional assessment

Table 1 Selected subcategor es and the r appl cat on to CDU soc al mpact assessment (abr dged vers on of full framework found n ES Table 1)[a]

Stakeholder	UNEP subcategory	Aims of UNEP subcategory assessment	Relevance to identified CDU assessment scope	Suggested indicator(s)	Typical data inputs used for assessing indicator	Suggested external data sources
Local community	Delocalisation & migration	Assess the contribution to delocalization, migration or 'involuntary resettlement' within communities	Changes in land use at scale for economic development can be a driving factor in the creation of displaced persons	Likelihood of forced evictions for technology implementation	Process design calculations, LCI data, geographical data (land use), regional/national data on forced resettlement/ compulsory purchase orders *etc.*	OECD land resources statistics
	Local employment	Assesses how an organization directly or indirectly affects local employment	CDU technologies could bring changes to employment opportunities both directly & indirectly, more so if the supply chain is localised	Operational impact on local employment – direct	Process design calculations, labour estimation calculations, employment & labour statistics	World Bank development indicators (employment), national employment & labour statistics
				Operational impact on local employment – indirect	Employment & labour statistics, IRENA employment statistics, COMTRADE-type data	World Bank development indicators (employment), national employment & labour statistics
	Access to material resources	Assess the extent to which organizations respect/protect/improve community access to material resources & infrastructure	CDU technologies can impact positively & negatively access to resources such as (renewable) electricity, water, land & other products. Additional	Operational impact on local land-use & zoning	Process design calculations, LCI data, geographical data (land use)	OECD land resources statistics
				Changes to local water supply & security	Process design calculations, LCI data,	UN AQUASTAT database, national

Table 1 (*Contd.*)

Stakeholder	UNEP subcategory	Aims of UNEP subcategory assessment	Relevance to identified CDU assessment scope	Suggested indicator(s)	Typical data inputs used for assessing indicator	Suggested external data sources
			strains on areas known to be water/land/energy (renewable & not) constrained may cause problems for communities.		water scarcity data for country/region	reports/statistics (regional perspective)
				Changes to local electricity & energy supply	Process design calculations, LCI data, national electricity/energy statistics (*e.g.*, DUKES)	World Bank WDI & SE4ALL databases, national reports/statistics on electricity & energy consumption/provision
			Operations may also impact access to material produce negatively (consuming limited resources) or positively (increasing domestic security of supply)	Changes to local access to material produce	COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases, observatory of economic complexity data
	Safe & healthy living conditions	Assess how organizations impact community safety & health	Potential risks and benefits of CDU plant operation on the communities safety & health should be assessed to determine potential impacts on the local community (considering both regular operation & accident potential)	Impact on air quality & pollution levels	Process design calculations, LCI data	World Bank WDI database
				Utilisation & risks associated with the use of hazardous substances in the operation	Chemical safety data, LCI data, HAZOP studies	COSHH database, ILO international chemicals safety cards database
Workers	Child labour	Assess whether the organization is employing child labour	Choices made in technology development/deployment may have	Potential for utilization of child labour in supply chain	Process design calculations, LCI data, COMTRADE-type data &	UN COMTRADE, EU PRODCOM & OECD databases, observatory

Table 1 (*Contd.*)

Stakeholder	UNEP subcategory	Aims of UNEP subcategory assessment	Relevance to identified CDU assessment scope	Suggested indicator(s)	Typical data inputs used for assessing indicator	Suggested external data sources
		as defined by ILO conventions & to identify the nature of any child labour	unintended consequences regarding child labour utilisation		national production/market statistics	of economic complexity data
	Forced labour	Assess whether there is the use of forced labour in the organization	Choices made in technology development/deployment may have unintended consequences regarding forced labour utilisation	Potential for utilization of forced labour in supply chain	Process design calculations, LCI data, COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases, observatory of economic complexity data
	Equal opportunities	Assess whether there is any worker discrimination present in the organization	Choices made in technology development/deployment may have unintended consequences regarding workplace discrimination	Potential for supporting discriminatory practices in supply chain	Process design calculations, LCI data, COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases, observatory of economic complexity data
	Worker H&S	Assess the rate of workplace incidents and prevention/management processes	It is widely understood there is a need to assess potential H&S risks in manufacturing	Risk to the H&S of workers associated with operation	ILO data on national workplace accident rate, HAZOP studies, chemical safety data	COSHH database, ILO international chemicals safety cards database, ILO H&S data

[a] The full unabridged version of the framework including all stakeholder categories can be found in the ESI Table 1.

previously mentioned. To provide an example of this assessment consider that the UNEP/SETAC guidelines include in the 'local community' stakeholder group subcategories for 'community engagement', 'cultural heritage' and 'respect of indigenous rights' all of which have been excluded from the CDU SIA framework. In each instance the importance that the technology choice has on the subcategory is low, and the importance of direct relationships is high (all three are characterised by an organisation's direct relationship with the local community and the decision to engage meaningfully with the community and respect its cultural heritage) this is largely dependent on organisational policy and behaviour. Table 1 forms the basis of the derived assessment framework, it provides a brief overview of the UNEP/SETAC subcategory aim and its perceived relevance to the SIA framework for CDU, alongside providing suggested indicators for each subcategory. Indicators for each subcategory are also supplied with typical data inputs that may be used in indicator calculation as the user sees fit and in most cases references to 'external' (*i.e.* not derived from the process) data sources that are generally open access. As discussed, the use of open access data in conjunction with process specific data allows for the broadest application of the framework without the need for costly databases, although in many instances LCI data is seen as beneficial.

Framework for SIA for CDU

SIA for CDU is applied by utilising the standard phases assessment structure as for LCA[49] and which has also been suggested for use in TEA.[9] By using a common assessment structure for LCA, TEA and SIA assessments, practitioners who are carrying out all three types of assessment have the advantage of using a common methodology and can share common inventory data as appropriate. Using a common phase structure also benefits the integration of assessments to create a triple helix for CDU.

For SIA, once assessment indicators have been established, the phases are applied for the analysis:

- Firstly, the goal and scope of the SIA are defined,
- The inventory is then compiled of process and supply-chain data along with identification of data sources for indicators,
- Impacts are assessed in accordance with the chosen indicators,
- Finally, the results are interpreted.

Together with the derivation of indicators these phases constitute a framework for SIA for CDU. The framework can be utilised to assess CDU technologies in a number of ways. Firstly, to compare deployment scenarios, secondly to compare different CDU technologies and thirdly to compare a CDU technology with a reference case or other routes to the same product.

Data collection for the inventory. CDU is not a standalone technology and many processes rely on several common core inputs, namely captured CO_2, low-carbon intensity electricity and green hydrogen to ensure that the environmental impacts are kept to a minimum. Therefore, the data for each of these sub-processes must also be collected for the inventory. In a similar way to LCA to enable fair and equitable comparison to a reference case or between products or scenarios, a functional unit is chosen to determine and model the product system. However, in contrast to LCA the impacts may not always be conveyed by functional unit as a mix of data types (quantitative, semi-quantitative and qualitative) are used. When dealing with qualitative indicators expressing impacts in terms of functional unit can be difficult, however, as the system modelling stems from the function unit, the link is present if not always explicit. When integrating an SIA with a LCA and/or TEA to form holistic assessment utilising the same functional unit for all assessments enhances integration by enabling a common inventory to be used. Some of the data required for the inventory is similar to that of an LCA or TEA, for example mass and energy balances or the estimated number of shift workers/employees needed. Further information on the sources of inputs (*i.e.* geographic location of raw (& manufactured) resource materials for catalysts) and data specific to the organisation is also required for impact categories such as child labour and migration.

Scoring within the framework. A major difference between SIA and LCA and TEA is how each indicator is assessed. In LCA the emissions flows are calculated then multiplied by a characterisation factor for a specific impact category giving a discrete number. In TEA indicators are calculated by adding impacts for example CapEx is calculated by adding together all capital costs throughout the process system. However, for SIA a number of factors must be considered in each indicator therefore, in many cases a discrete numerical indicator based on summation cannot be calculated. This is due to data in the inventory being of mixed type, quantitative, semi-quantitative and qualitative. Therefore, a qualitative scoring methodology which is based on quantitative and semi-quantitative data can be derived to allow the comparison of indicators. The scoring methodology for each indicator and within each example assessment is individual (goal and scope specific) and consists of data from numerous sources. Therefore, although scores for a single indicator can be compared within an assessment, the scores for a specific indicator cannot be compared to those from a separate assessment *i.e.* scores in example 1 below cannot be compared with example 2. Scores that utilise world rankings or comparisons as part of the data calculation method, utilise this data in a relative fashion to the world ranking. It should be noted that the expected relationship between scale and marginal impact is not linear, suggesting that the larger your deployment scale is the higher your scores can be and the more problematic high scores may be in terms of barriers to deployment. Scoring should be applied with a scale with enough granularity to see differences in results to enable hotspot identification therefore, a three-point scale is not recommended, rather five- or nine-point scales. The use of colour through traffic-light systems can aid scoring and enable visual interpretation of results.

Impacts for social assessment can be positive, negative or neutral in nature depending on the specific wording of the indicator with scores given in relation to the specific scenario (or reference scenario, if required). Therefore, care needs to be taken when deriving scoring methods for the framework to ensure consistency in scoring. For example, a decision needs to be taken as to whether a zero score indicates a positive result *i.e.* no social impact or a positive social impact or whether a high score indicates this. For example, in the presented examples below, for the indicator 'changes to local access to materials produced', a very high change results in a zero score as this reflects self-sufficiency (a reduction on reliance of imports) as production is increased locally. However, one might expect a very high change to result in a high numerical (score 4 in the examples) scoring rating. Subsequently, careful consideration of how the scoring methodology is derived is needed to ensure consistency and no 'false positive' hotspots are identified. Here, a colour system can help by clearly identifying negative impacts.

Results: demonstration of the framework

Here we provide two examples to demonstrate the application of the framework to identify hotspots for new CDU processes. These examples show how data should be collected and utilised within the framework, how scoring can be derived and how results can be interpreted to identify hotspots. The indicators selected are those described in the Methodology section. Three commonly discussed CDU technologies from literature were chosen to demonstrate application in different technology areas:

- Methanol production from CO_2 and H_2 *via* water electrolysis[50]
- Polyol production for polymers[51]
- Mineral carbonation of waste ashes to produce construction blocks[52]

Social impacts are not solely reliant on the process; the location scenario will also have an effect. To demonstrate how impacts can vary between countries for the same process, three locations for assessment have been selected: the UK, China and Chile. These locations are diverse in many areas *i.e.* in respect to population, environmental policy and renewable energy production. Hydrogen production is key for a number of CDU processes and the IEA[53] has highlighted China and parts of Chile amongst other countries as promising areas for H_2 production based on costs from hybrid solar photovoltaic and onshore wind systems. It is presumed that the supply chain for each scenario will be predominantly within the scenario country, however, some primary resources are geographically restricted, and therefore the most likely sources of supply should be taken into account.

Goal and scope of examples

Example 1: the goal is to conduct a comparative assessment to determine the social impact hotspots for the production of methanol (MeOH) in three locations (UK, China and Chile) in 2020. In conjunction with varying production location, the supply of electricity for the process will be investigated considering wind and solar power.

Example 2: the goal is to compare social impacts of utilising 1 tonne of captured CO_2 for different CDU technologies, namely methanol production, polymer production and mineral carbonation in the UK with varying energy sources (wind or solar) in 2020. To identify hotspots within the process and supply-chain and to identify which has the least social impact.

Inventory data collection

Data for each process and sub-process was collected from literature and can be found in ESI, Table 2.† The further data sources regarding country specific data are listed in the full impact calculation tables which can also be found in the ESI.†

Table 2 Results of SIA of methanol production in three locations

Subcategory	Indicator	MeOH UK wind	MeOH UK solar	MeOH China wind	MeOH China solar	MeOH Chile wind	MeOH Chile solar	Justification
Delocalisation & migration	Likelihood of forced evictions for technology implementation	0	0	1	2	1	1	Reasonably low risk of displacement for economic development, wind needs larger area though likely offshore. Forced eviction most prevalent in Asia followed by Latin America
Local employment	Locals directly employed due to activity	1	0	1	0	1	0	Higher job creation in solar energy than wind (×2–3 times greater per MW)
	Locals indirectly employed due to activity	1	1	1	1	1	1	Localised supply apart from catalysts
Access to MR	Changes to local land use	1	4	2	1	2	1	China and Chile have considerable prospects for solar deployment. UK has access to large wind resources, though land for solar an issue
	Changes to local water supply & security	2	2	1	2	2	2	China has low level of people living in water scarce areas (36%). UK and Chile are higher (46% and 52% respectively)
	Changes to local electricity supply	2	3	1	1	4	3	Electricity demand for MeOH production is high due to water electrolysis for H_2. China has least capacity issues, UK wind has greater potential for expansion. Solar & wind capacity are small in Chile, where hydro is dominant renewable energy source
	Changes to local access to material produced	2	2	2	2	4	4	Chile exports large amount of methanol. UK and China import more methanol than they export so this will increase local security of supply
Safe & healthy living conditions (LC)	Impact on air quality/pollution levels – production	0	0	2	2	1	1	Air pollution is worst in China and best in UK. The amines from the capture process will add to local air pollution
	Utilisation of hazardous substances in process	2	2	2	2	2	2	Use of amines and H_2 (H_2 needs storage)
Promoting social responsibility	Use of wastes and other sustainable materials	1	1	1	1	1	1	Inputs are sustainable as renewable H_2 production is used, however electrodes use platinum group metals
	Social responsibility in supply chain	1	1	1	1	1	1	Platinum group metals used but sustainable reporting is common for the metals therefore sustainable producer could be chosen
Consumer health & safety	Consumer health & safety risk	2	2	2	2	2	2	Methanol predominantly used in industry rather than by consumers, however poses acute health hazards for oral, dermal and inhalation toxicity and is highly flammable
EOL responsibility	Recyclability of product & process elements	3	3	3	3	3	3	Methanol is not a product able to be recycled directly at end of life will emit CO_2. Can be recycled by air capture of CO_2
	Potential health risks for improper disposal of product & process elements	1	1	1	1	1	1	No issues for product disposal, high use of electrolysers for H_2 = disposal of used electrodes
Child labour	Potential for utilization of child labour in supply chain	0	0	0	0	1	1	Chile has low levels of child labour though these are mainly concentrated in the services and agricultural industries
Forced labour	Potential for utilization of forced labour in supply chain	1	1	1	1	1	1	Higher risk in Africa, Asia and Pacific. Metal catalysts likely to be sourced from Africa however quantities needed are low.
Equal opportunities	Potential for supporting discriminatory practices in supply chain	0	0	1	1	0	0	UK and Chile have high levels of female employment. China has much lower levels of employment which could lead to discriminatory practice
Worker health & safety	Worker health & safety risk	2	2	2	2	3	3	H_2 storage & transportation and possible exposure to amines are biggest issues regarding H&S. UK has a better H&S Chile. Unknown for China
Public commitment to sustainability issues		1	1	2	2	2	2	Chile has very high renewable energy targets, but with China is lower in the Global sustainable competitiveness ranking than UK
Prevention & mitigation of conflicts	Potential for utilisation of goods/materials/services	1	1	1	1	1	1	All countries would likely be sourcing metals externally therefore rankings similar
Contribution to economic development	Use of local supply chain	1	1	1	1	1	1	Raw materials apart from metals can all be sourced locally, only CO_2 and water required

Impact calculation and interpretation example 1: comparative assessment of scenarios/locations

For the first example, the production of methanol (MeOH) in three locations (UK, China and Chile) is compared using a functional unit of 1 tonne of methanol. In conjunction with varying production location, the supply of electricity for the process was also varied between wind and solar power. Scores were calculated for each indicator using a five-point scale and a summary is shown in Table 2. A more detailed version of Table 2 can be found in the ESI which details the data sources and scoring mechanism.†

The highest scores (hotspots) were observed in categories where the electricity supply contributes strongly to the scoring, hence indicating electricity supply is

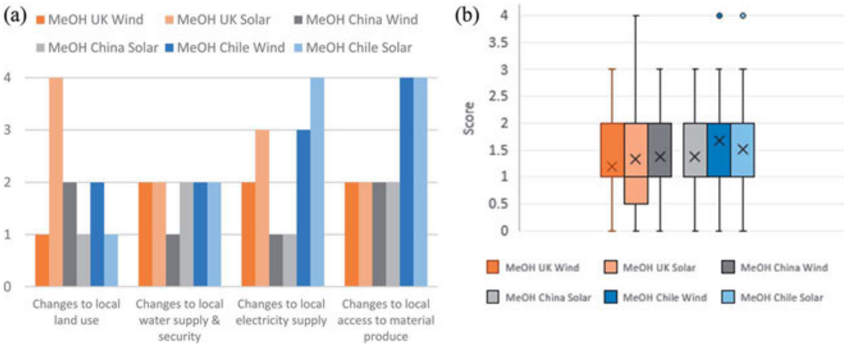

Fig. 2 (a) Comparison of access to material resources indicators. (b) Distribution of score for methanol production.

a significant social impact hotspot. Indicators where the process has a greater contribution than the location broadly result in the same score across all locations. Significant differences in scoring can be observed in the subcategory of 'access to material resource' where the effect of the large electrical energy requirement for the production of H_2 has a significant impact on the indicators for land use and changes to electricity supply (Table 2 and Fig. 2a). Solar and wind energy contribute 23% and 14% respectively to Chile's renewable energy capacity,[54] therefore in these scenarios the large amounts of electricity required could place significant strain on capacity and are hence identified as a hotspot. Looking at alternative sources of low carbon or renewable energy in Chile could reduce the social impacts. Chile exports significantly more methanol than it imports, indicating that increasing production would not positively impact the indicator 'changes to local access to material produced', whilst higher imports in the UK and China could lead to greater security of supply by deploying a CDU methanol plant.

Overall, the impacts for methanol production in each scenario are reasonably low or positive in nature. Fig. 2b highlights the dispersion of the results for each scenario. Across all scenarios the median score is 1, with methanol production using wind power in Chile indicating the highest mean for social impacts. Production in the UK *via* solar power shows the widest variability of scores, whilst production in Chile has a smaller variability but with outlying high scores. Due to the screening nature of this style of SIA, it is the outlying high results, those with the highest median scores and those with the largest range in the 50 to 75% and 75% to max quartiles that should be carefully considered to determine how the impacts could be mitigated.

Impact calculation and interpretation example 2: comparative assessment of technologies

In example 2, different CDU technologies are compared in a deployment scenario of the UK, here a functional unit of 1 tonne of captured CO_2 converted to a product is used to compare diverse technologies. One tonne of CO_2 would produce 0.68 t methanol, 4.4 t polymer or 11 t of mineralised carbonated block. In this assessment the plant location contributes equally across each indicator with

Table 3 Results of SIA comparing production of methanol, polymers and minerals for construction in the UK utilising 1 tonne of captured CO_2

Subcategory	Indicator	MeOH UK wind	MeOH UK solar	Polymer UK wind	Polymer UK solar	Mineral UK wind	Mineral UK solar	Justification
Delocalisation & migration	Likelihood of local forced evictions for technology implementation	0	0	0	0	0	0	Highly unlikely in UK scenario, most land used for MeOH solar but this likely to be agricultural land
Local employment	Locals directly employed due to activity	1	0	3	3	3	3	Higher job creation in solar energy than wind (×2–3 times greater per MW), however polymer and minerals use much lower levels of renewable energy
	Locals indirectly employed due to activity	1	1	1	1	0	0	Localised apart from catalysts, for mineralisation use of waste local materials
Access to MR	Changes to local land use	2	4	1	1	1	1	UK has access to large offshore wind resources, though land for solar an issue. Electricity demand for MeOH is 13–30 times greater than for polymer or mineralisation production
	Changes to local water supply & security	2	3	0	0	0	1	Minimal water needed for polymers and minerals though solar can have high water demand per MW h. Green H_2 production for MeOH requires water
	Changes to local electricity supply	2	2	0	0	0	0	MeOH has higher electricity demand due to H_2 production (13–30 times more than polymers or mineralisation)
	Changes to local access to material produced	2	2	3	3	4	4	More methanol is imported than exported, polyurethane imports and exports are similar therefore increased local production will have limited impact. Mineral imports are lower therefore increased local supply will have little impact
Safe & healthy living conditions (LC)	Impact on air quality/pollution levels – production	0	0	0	0	1	1	Mineralisation has potential to be carbon negative technology reducing CO_2 levels
	Utilisation of hazardous substances in process	2	2	0	0	0	0	Use of amines and H_2 (H_2 needs storage) for MeOH. Much lower level of amine needed for polymers and minerals
Promoting social responsibility	Use of wastes and other sustainable materials	1	1	2	2	0	0	Mineralisation uses wastes as feedstocks, methanol uses some platinum group metals for electrolysis, polymers use more materials that could be sourced from fossil resources, care needs to be taken to reduce this
	Social responsibility in supply chain	1	1	1	1	0	0	Metal catalyst and electrode metals have very low possibility of being sourced illicitly or from conflict areas
Consumer health & safety	Consumer health & safety risk	2	2	0	0	0	0	Methanol predominantly used in industry rather than by consumers, however poses acute health hazards for oral, dermal and inhalation toxicity and is highly flammable
EOL responsibility	Recyclability of product & process elements	3	3	2	2	0	0	Methanol is not a product able to be recycled directly is going to emit CO_2, can be recycled by air capture of CO_2. Polymers recycled until end of life. Minerals do not need recycling, though can be crushed and reused
	Potential health risks for improper disposal of product & process elements	1	1	0	0	0	0	No issues for product disposal, high use of electrolysers for H_2 = disposal of used electrodes
Child labour	Potential for utilization of child labour in supply chain	1	1	0	0	0	0	MeOH uses high level of catalyst/rare metals which can be sourced from areas using child labour
Forced labour	Potential for utilization of forced labour in supply chain	1	1	0	0	0	0	MeOH uses high level of catalyst/rare metals which can be sourced from areas using forced labour
Equal opportunities	Potential for supporting discriminatory practices in supply chain	1	1	1	1	0	0	Not likely in UK however could play a factor within supply chain of metals for catalysts
Worker health & safety	Worker health & safety risk	2	2	1	1	1	1	H_2 storage & transportation and possible exposure to amines are biggest issues regarding H&S for MeOH
Public commitment to sustainability issues		1	1	2	2	1	1	MeOH could be included in renewable energy targets and help with grid balancing, mineralisation can count towards net zero targets as a carbon dioxide sink
Prevention & mitigation of conflicts	Potential for utilisation of goods/materials/services	1	1	0	0	0	0	High level of catalyst used for MeOH which may be sourced from unstable regions
Contribution to economic development	Use of local supply chain	1	1	2	2	0	0	Mineralisation recycles waste products, MeOH predominantly local supply chain though catalysts not local, PO may be externally sourced for polymers

the process and supply chain varying. Indicators are again calculated using a 0–4 point scale and a summary is presented in Table 3 with further details on scoring available in the ESI.† Here, in general a smaller variation in scoring between each technology was observed than in example 1 (Table 3), thus, indicating the deployment scenario can be play a significant role in SIA for CDU. Comparing indicators only in the scenario with wind energy, the largest variation occurred in the ‘recyclability of product & process elements’, ‘changes to local access to material produce’ and in ‘land use’ (Fig. 3a). When the average score is considered for each subcategory in the scenario with wind energy it was observed that methanol has the highest impact in seven subcategories (Fig. 3b). Similarly to example 1, ‘access to material resources’ is a significant indicator hotspot along with local employment. However, it should be remembered that a high score

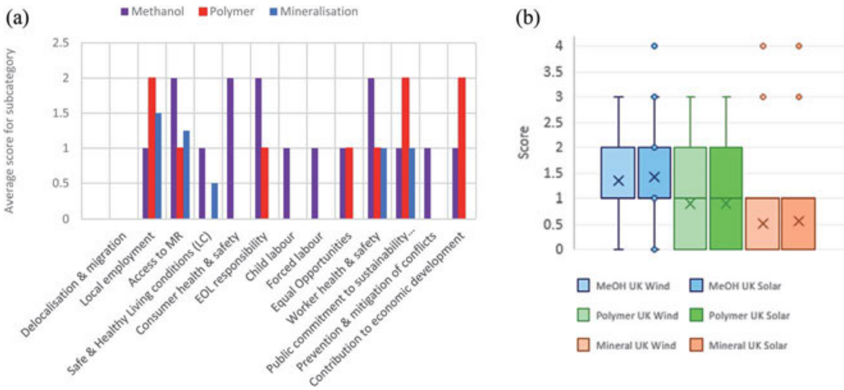

Fig. 3 (a) Social impact scores of CDU technologies in UK using wind energy. (b) 6 variance of scores for CDU technologies in UK.

indicates a hotspot and therefore a high score in local employment reflects few jobs being created. Averaging the indicator scores for each technology option, it was observed that methanol has greater potential for negative social impacts, and mineralisation the most positive impacts. This result was not unexpected as power to X technologies such as methanol utilise large amounts of renewable energy and produce products which have potential health and safety issues factors which can have social impacts. The only indicator with no variation across all three technologies is 'delocalisation and migration'. This indicator is from the stakeholder group of 'local community' therefore, it reflects the process location not the whole supply-chain. Hence, with one location no variation was observed.

Discussion

This framework provides the first steps in developing a methodology for SIA for CDU. By adapting the UNEP/SETAC guidelines for S-LCA (which focus on the assessment of products and organisations) to emerging CDU technologies, a comprehensive SIA screening methodology has been developed. The framework is designed to be adaptive to the practitioner's needs and focuses on the process and deployment scenario rather than the organisation. By using this approach, organisational specific impacts such as decision making around corporate responsibility policies are not included in the analysis, as these impacts are highly specific to individual organisations. However, this framework can highlight issues with certain processes inputs due to known unsustainable practices or negative impacts which could be mitigated by organisational choices. For example; palm oil is only produced in certain countries and there are known sustainability issues; the same is true of a number of metals used in catalysis. Therefore, by flagging these as a hotspot to be addressed in process development alternatives feedstock options could be explored or guidance given to ensure sustainable supply, hence reducing social impact as much as possible. Demonstration through the examples has shown the framework can be used to assess a single technology with various process options and deployment scenarios or used to compare different CDU technologies. Further purposes could include assessing a CDU technology and comparing it with a reference case or other production routes for example *via* biomass.

By focusing the framework on emerging CDU technologies and specifically their process and deployment scenarios, some UNEP/SETAC subcategories and indicators were discarded due to lack of relevance. This leads to a streamlined screening assessment whereby effort can be focused on priority areas for process development research. However, this does not negate the importance of the inclusion of these subcategories if a full S-LCA assessment is desired by an organisation on a deployed technology.

The scoring methodology requires multiple aspects to be taken into consideration for each indicator. In many cases the supply chain as well as the process deployment scenario and scale of deployment all contribute to the total impact and the practitioner must exercise judgement as to how each aspect is considered. This frequently occurs throughout the framework (particularly where COMTRADE or PRODCOM type statistics are used as data sources). An example of this is how the scoring of child labour indicator in 'CDU methanol in the UK using wind power' example case is derived. Using this indicator as an example two aspects can be discussed, firstly as to how the assessment process is derived and secondly to demonstrate the advantages and limitations of such an approach. The indicator utilises a combination of key data sources:

(1) Process data for the CDU methanol plant, including mass and energy balance data

(2) LCA database datasheets for the relevant material inputs, including where possible infrastructure (in this example, the construction of the wind turbines is also considered). In instances where this data is not available to the assessor estimations from available literature data will be required

(3) COMTRADE/PRODCOM type data that allows for the determination of material (mass/volume units) and value (currency units) flows by harmonised system coding (HS codes), to either the 4-digit or 6-digit level where applicable. In some instances, for materials such as fossil fuels and primary electricity, additional data sources with more granularity may be viable to augment or use in place of trade data (*e.g.* the digest of UK energy statistics – DUKES)

(4) World Bank statistics on the required assessment subject (*e.g.* child labour)

Utilising the above data, the aim of the assessment is to trace material inputs to their initial extraction from the environment. This begins with gathering all relevant data on the process and a consideration of the whole value chain (from primary material extraction to end of product life) to determine which elements are key to assessment. A similar approach can also be taken tracing the product to end of life if necessary, as an addition or an alternative. The process data are used to identify key process inputs, with this then coupled with the LCA datasheets to trace inputs back to extraction or an identified cut off point. Where inputs such as heat and electricity are used, the assessor should determine the likely provider of these and factor this into the process. Identified material inputs required for production can then be traced to their likely origins using COMTRADE data. COMTRADE data allows the assessor to examine global trade flows of materials, allowing for an estimation to be made on the materials likely origin for a specific location, such as the UK. This then allows for a qualitative assessment to be made on the risk of encountering negative social impacts through the supply chain: in this specific example the utilisation of child labour. It is recommended that not all material inputs are traced fully, as this will likely be a resource intensive process for diminishing returns. Given the scope of this framework and its intended audience there is likely to be a significant level of uncertainty as to exactly where a material is sourced from in the supply chain. This is expected, considering the previously discussed example of illicit gold mining where it was stated that supply chain complexities were a problem for even large multinationals, but ultimately leaves an inherent element of uncertainty in the analysis. Given the complexities of global trade it is also impractical to assess all exporters of a given material to a country: for example, UN COMTRADE data on United Kingdom imports of HS 7604 (aluminium; bars, rods and profiles) in 2018 returns a total of 53 individual country entries, covering a global import of 148.2 kt of material with a total trade value of $620 million. Ultimately a cut-off is likely to be needed, with the assessor presented with the choice of determining whether to use a value or mass/volume. It should be noted that these options may result in differing lists of countries for assessment. For example, continuing with the prior consideration of HS 7604 in the UK, imports from China account for 29.8% of mass but only 17.0% of trade value.

A demonstration of how this method can be applied is shown in Fig. 4, where a partial study is illustrated investigating the potential risk for child labour in the production of aluminium to be used in a wind turbine for the CDU methanol example included in the Results section. All other elements of the study have been substituted out for ease of illustration. Fig. 4 shows the breakdown of each stage into specific elements as described above from process data and LCA datasheets. At each stage the risk of the utilisation of child labour can be assessed in parallel, with the number of stages ultimately determined by the cut-off criteria selected by the user – in this case the importation of aluminium or its ore for manufacturing a wind turbine in Germany.

The example in Fig. 4 shows clearly the relative ease of application of the framework; however, it does also highlight the main limitations of the approach

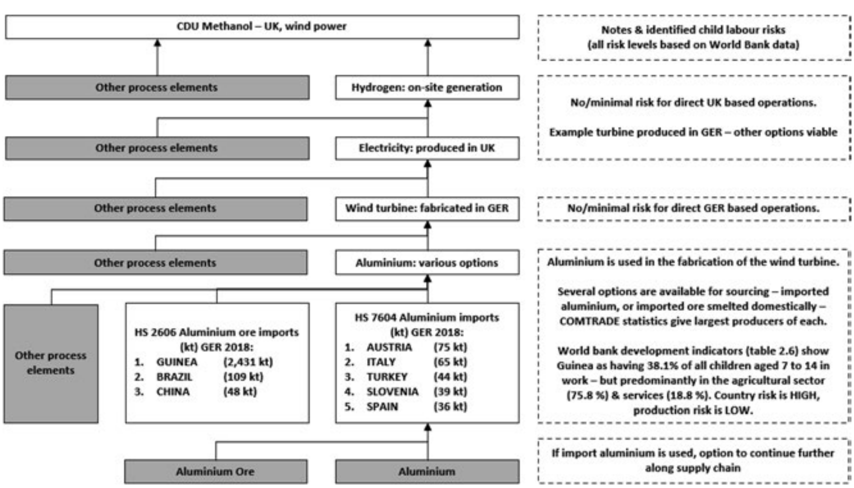

Fig. 4 Illustrative example of framework application, using World Bank data and UN COMTRADE data.

that have been previously mentioned. The first is that for every level of assessment there is a broadening number of process elements to consider – each with potentially complex supply chains. Whilst individual process element assessments may be relatively quick, the potential for exponential growth is problematic.

Secondly, the assessment result remains relatively uncertain. Whilst ore imports for aluminium are dominated by Guinea, the picture for aluminium itself is more complex (the five countries included in the figure are the dominant by mass, but the rest of the top 10 supply more than 20 kt of material and the HS codes, even when taken to the 6-digit level, may not allow for a narrowing of suppliers even for specific materials). In some instances, data may also be missing if it is not reported to the UN – in the example above no COMTRADE data are available on whether all Guinean exports to Germany are mined within the country or are imported from elsewhere (although this data may be available in other databases). However, as stated in the research question the aim of this framework is to primarily augment sustainability assessment and decision analysis for CDU technology development, given the relative ease and significant overlap in data required to conduct other CDU technology assessments such as LCA and TEA it is fit for purpose as a screening-type approach.

The framework can be further developed by the practitioner to include multi-criteria decision analysis (MCDA) to provide preferencing or weighting to specific criteria. In the presented examples weighting was not included, therefore all indicators have been given equal importance. This approach is useful for identifying hotspots for decision makers to then consider how significant the impacts are in relation to the overall social impact of the process. However, it does not put any emphasis on the significance of the impact on humans, for example an impact that could cause significant harm to health or even death would be given the same importance as one that benefited employment. By adding weighting/MCDA to the assessment a greater level of nuance can be added to the assessment and so this approach should be considered when the methodology is applied. However, it should be noted that MCDA/weighting is entirely specific to the goal and scope of the study and the aims/priorities of the study commissioner and decision makers. Therefore, results from such studies should only be considered in the context to which they were applied.

Conclusions

Social impact assessment needs to be included in the analysis of CDU technologies to ensure holistic sustainability assessment. SIA forms the third strand of a triple helix assessment approach encompassing economic, environmental and social impact. The presented framework enables practitioners to conduct SIA screening of emerging CDU technologies by identifying hotspots both within the process and the deployment scenario. The framework is a first step in enabling practitioners to include social impacts in CDU technology assessment. Its application to a range of CDU technology cases studies will enable further refinement of the methodology.

It is concluded that raw materials contribute significant social impacts within CDU and therefore, careful consideration of sources is required. Depending on the technology, differing stakeholder groups are impacted to differing degrees.

Therefore, it cannot be concluded that one stakeholder group is most important in CDU; all should be investigated. In particular, when assessing technologies that have a significant H_2 requirements, as is the case for many power to X technologies within CDU, the social impact of the demand for considerable quantities of renewable energy must be carefully considered. CDU technologies can have positive social impacts particularly in regard to reducing CO_2 emissions and the use of wastes. These benefits can be seen within the impact categories focusing on health and safety. Impacts concerning employment and labour are complex to assess due to most impacts being within the supply chain, however risks should be highlighted. Both positive and negative impacts can be observed, with increased high value job creation as pay for chemical plant jobs was found to be higher than the national average however negative impacts can occur if care is not taken in sustainably sourcing metal catalysts and other raw materials.

This framework could further enhance CDU assessment by integrating with LCA and TEA to form a triple helix of assessment. By integrating these assessments, hotspots and potential trade-offs within the process from economic, environmental or social perspectives can be identified for consideration. If this integration is further expanded to include multi-criteria decision analysis through weightings or optimisation, decision making for process design can be enhanced and trade-offs between aspects explored.

Author contributions

Stephen McCord: conceptualization, methodology, formal analysis, investigation, data curation, visualisation, writing – original draft, writing – review & editing; Katy Armstrong: conceptualization, methodology, formal analysis investigation, data curation, visualisation, writing – original draft, writing – review & editing; Peter Styring: supervision, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

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8 Barriers for SME's in CO_2 Utilisation

This chapter explores the barriers and opportunites facing small and medium sized enterprises (SME's) in CO_2 utilisation. SME's are key to the economy and growth. Within CO_2 utilisation many technologies are at research and demonstration stage within university or SME settings. It is well documented that technologies can struggle to overcome the barrier of the so called 'valley of death' where technogies need increasing levels of funding to progress through development stages. Barriers to the general success of SMEs have been identified in the fields of policy/regulation, LCA studies, financial knowledge, and external links. The survey conducted with SME's in the CO_2 utilisation sector confirmed these is issues are apparent within the sector. Significant barriers for SME's were found to be regulation, lack of funding/subsidies from government, investment and public funds, lack of partners and the CO_2 price. Recommendations of stategies to tackle these barriers are presented to enable the full potential of CO_2 utilisation SME's, to be realised.

8.1 Introduction

As technologies develop from ideas to research, research to demonstration and then to full deployment many different sized organisations can be involved. Small and medium sized enterprises (SMEs) play an important role in the economy. The European Commission states that:

> *"Small and medium-sized enterprises (SMEs) are the backbone of Europe's economy. They represent 99% of all businesses in the EU. In the past five years, they have created around 85% of new jobs and provided two-thirds of the total private sector employment in the EU. The European Commission considers SMEs and entrepreneurship as key to ensuring economic growth, innovation, job creation, and social integration in the EU."*[1]

Therefore, understanding issues that SMEs face and providing support can encourage growth (European Commission, 2011). However, to achieve this the issues must first be identified.

Sustainable development within the chemical industry provides many opportunities for entrepreneurship and therefore SME's. However, it also raises challenges with regard to policy, funding and knowledge transfer (Jenck *et al.*, 2004; IEA, 2009; Hockerts *et al.*, 2010; Pacheco *et al.*, 2010; Bakshi, 2011; Fernández-dacosta *et al.*, 2017). Within the field of CO_2 utilisation, Zimmermann and Schomäcker, 2017, identified that the majority of activities were at the research and demonstration and small market scale indicating the involvement of SME's. Market growth in CO_2 utilisation is observed from large corporations with research capabilities such as Bayer, BASF or Saudi Aramco and from SME's via new start-ups and spin-offs from Universities commercialising research findings. Examples of these university spin-offs in the field of CO_2 utilisation include – Carbon8 Systems (The University of Greenwich, UK), Novomer (Cornell University, USA), Carbon Capture Machine (Aberdeen University, UK). The IEA, 2019 has reported that over 1 Billion USD has been invested in global private funding for CO_2 use startups (IEA (International Energy Agency), 2019), signifying the level of interest in CO_2 utilisation startups. Therefore, understanding the influences that effect deployment of CO_2 utilisation technologies can give insight to accelerating the deployment and CO2 utilisation reaching it's potential (Wilson *et al.*, 2015; Kant, 2017).

Within literature barriers and aids to SME's development have been identified. Heidrich and Tiwary, (2013) ascertained that SME's can struggle to conduct life cycle analysis studies (LCA) to determine the environmental impacts of their products. For companies wishing to substantiate their sustainable and green credentials, LCA is a vital tool. Heidrich and Tiwary, 2013 highlighted particular key issues in the lack of understanding of LCA and accessibility to data. Finance is commonly identified as a key issue

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[1] https://ec.europa.eu/growth/smes

and can take numerous forms. Beck, Demirgüç-Kunt and Maksimovic, (2005), determined that financial constraints have a higher impact on the growth of small enterprises than larger ones. The barriers effecting the access of SMEs to European Funding mechanisms are highlighted in Gilmore, Galbraith and Mulvenna, (2013) and include administrative, internal and financial issues. It has been acknowledged that by having external links to increase knowledge and skills, the growth of SMEs has been aided (Hoffman *et al.*, 1998; Zeng *et al.*, 2010; Michaelides *et al.*, 2013). Through conducting a survey of SME's involved in CO_2 utilisation, it is investigated as to whether these generically identified barriers also specifically affect the development and deployment of CO_2 utilisation technologies. The need for such work has been highlighted by my previous work in the SCOT Project Strategic Research and Innovation Agenda (SERIA) and Joint Action Plan (JAP) (Armstrong *et al.*, 2016; Wilson *et al.*, 2016). Whereby, is recommended that an understanding of the factors preventing companies from deploying CO_2 utilisation technologies can help remove these barriers though policy changes and industrial collaboration. The aim of this work is to identify if such barriers exist and where they lie for SMEs in the CO_2 utilisation sector.

8.2 Methodology

A questionnaire based survey was designed to focus on the factors that are inhibiting SMEs of less than 250 employees from implementing technologies that use alternative carbon sources such as CO or CO_2 and compare these factors with larger companies. The survey was open to all sizes of organisation, although specifically targeted small and medium-sized enterprises (<250 employees) in order to ascertain if there are certain barriers specifically inhibiting SMEs from development and growth in the sector. The survey was designed and deployed using Survey Monkey software[2] and was conducted in accordance with the Ethics Policy of the University of Sheffield. A full list of the questions can be found in Appendix 1. The survey was designed to capture the thoughts of a wide range of stakeholders who either have alternative carbon-based products on the market, are at an advanced technology readiness level, are interested in the sector due to symbiotic opportunities created by by-products/wastes or are research organisations looking to create spin-off companies in the sector. In conjunction with studying the barriers the respondents felt were inhibiting implementation, the survey also assessed the drivers that have or could increase interest in alternative sources of carbon.

[2] www.surveymonkey.com

The survey utilised the CO2Chem network The survey was sent to over 250 contacts and posted to social media via CO2Chem and the SusChem networks. The survey was open for 6 weeks in autumn 2017 and attracted 51 responses (39 full responses and 12 partial responses). Partial responses were received where the respondent answered the first half of the survey only; these questions related to the respondent's organisation and whether it was interested in alternative carbon sources. The partial respondents did not answer the questions relating to knowledge of CO/CO_2 utilisation or the factors affecting their organisation's decisions to implement the technologies. All statistical analysis conducted on the answers is based on the total number of responses to that particular question (i.e. 51 or 39).

The survey was structured into three main parts:

- Introductory demographic questions: characterisation the respondent's organisation by size, sector and other descriptors.
- Motivation questions: identification of participation in networks and external organisations and environmental goals.
- Main questions: questions relating to CO_2 utilisation including familiarity, interests and barriers.

Questions styles within the survey included demographic questions, dichotomous questions, single select multiple choice or multi-select multiple choice question, 5 point Likert scale questions and free text. In the first part organisations answered questions to describe their demographic, enabling the responses to be categorised into demographics such as sector or size of organisation. Examples of questions included 'How many employees does your organisation have?' with a single select multiple choice answer to ascertain if SME or larger company. Respondents were also asked to identify which sectors their organisations operated in, multiple answers could be given as it was recognised that companies may opperate in a number of sectors. This question was included to determine if there was a difference in responses between sectors. Respondents were given the following options:

- Chemicals
- Minerals/Construction
- Fuels
- Metals
- Bio-based
- Waste
- Energy
- Other

Respondents were also asked to classify what Technology Readiness Level (TRL) their organisation worked at. TRLs are used to convey how mature a new technology or process is on the pathway to full commercial operation. TRLs are used by many organisations, governments and funding bodies as a simple scale to enable decision making and classification of activities. The definitions of each TRL as used in H2020[3] are given below (Table 8-1). This question was used to determine if there was a significant difference in the TRL between small and large companies, and if TRL influenced certain barriers to implementation. TRLs can be grouped into 4 basic categories – research, pilot scale, demonstration scale and commercial; for ease, respondents were asked in which of these four TRL categories activity occurs. Many companies operate over a range of TRL levels therefore could respond in multiple categories.

Table 8-1. Technology Readiness Levels as defined by H2020

Technology Readiness Level	Description	TRL Grouping
TRL 1.	basic principles observed	Research
TRL 2.	technology concept formulated	
TRL 3.	experimental proof of concept	
TRL 4.	technology validated in lab	Pilot
TRL 5.	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	
TRL 6.	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	Demonstration
TRL 7.	system prototype demonstration in operational environment	
TRL 8.	system complete and qualified	
TRL 9.	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)	Commercial

As previously discussed membership of external organisations can be beneficial to the success of SME's. Therefore, to ascertain if participation in organisations, networks, specific CO_2 related funding schemes or involvement in knowledge transfer and advocacy had any impact within CDU, respondents were asked '*Please indicate if any of the below listed points apply for your organisation? Please select all that apply:.*

- *Member of Spire;*
- *Member of Cefic;*
- *Member of Eurofer and/or Eurometaux;*
- *Member of The European Cement Association;*
- *Member of Hydrogen Europe and/or European Hydrogen and Fuel Cell Association;*
- *Member of CO2Chem or CO2 Value Europe*

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[3] https://ec.europa.eu/research/participants/portal/desktop/en/support/faqs/faq-2890.html

- *Have participated in the German funding programme on CO2 utilisation*
- *Member of KIC's (e.g. Climate, Energy, Raw materials)*
- *Member of BBIC (Bio-based industries consortium)*
- *Other CO/CO2 or low carbon related organisations (please specify)*

As the list is non-exhaustive, though covers the main groups within Europe, a free text 'other' option was included.

Within the main body of the survey, scaled-response questions were asked to ascertain knowledge/familiarity in certain areas or to assess the impact of particular barriers. Questions were structured to cover the main generic barriers identified within the literature i.e. finance, LCA, specific knowledge related to CDU. Examples of these include:

- *On a scale from 1 (never heard of) to 5 (extremely familiar), please rate how familiar you are with carbon dioxide utilisation*
- *On a scale from 1 (never heard of) to 5 (extremely familiar), please rate how familiar you are with these specific CO_2 utilization technologies. Please answer for each option.*
- *To what extent do the following factors prevent your organisation from implementing technologies to use alternative sources of carbon to their full potential? Scale of 5 options from 'very high extent' to 'not at all'*

Here, the use of predefined answers within an incremental scale was employed to determine how strongly the participant felt about the issue. The use of scales enabled comparision between responses between organisation size and sector to determine if one demographic was more impacted than another.

8.3 Results

8.3.1 Demographic

To ascertain whether barriers were perceived as being geographically-based, respondents were asked where their organisation was based and in which countries it operated. Forty eight respondents were based in the EU with 3 from Canada. The spread of responses can be seen in Figure 8.1. This geographical spread is unsurprising as mailing lists from the CO2Chem network, which has a membership that is roughly split 50% UK 50% rest of Europe. The survey was also advertised via twitter and Facebook which resulted in the responses from outside the EU, which was unexpected.

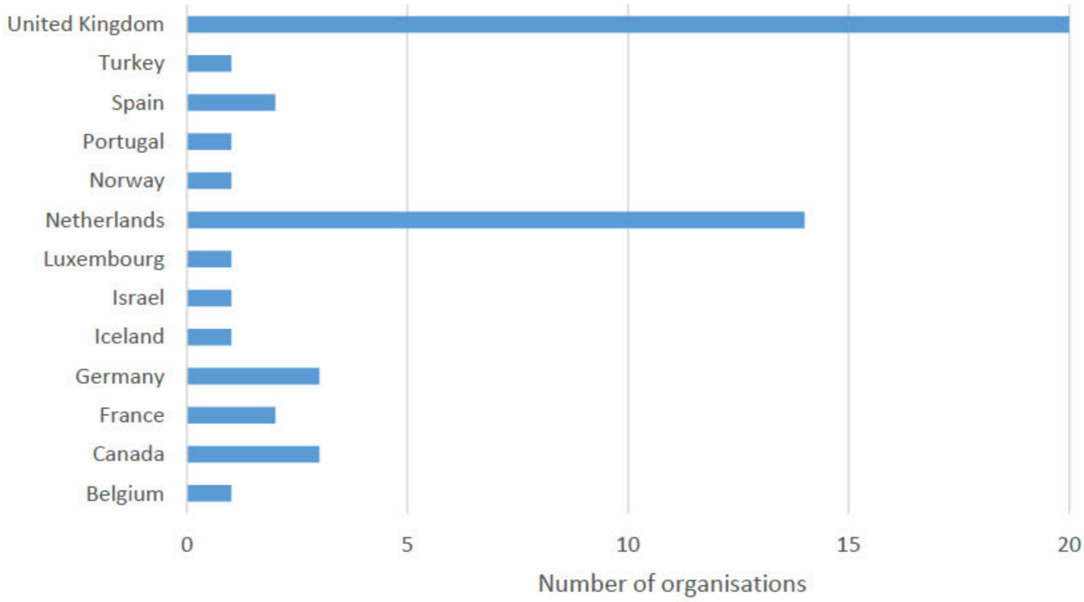

Figure 8.1 Base location of organisations

The survey was open to all sizes of organisation, although it specifically targeted small and medium-sized enterprises (<250 employees) in order to ascertain if there are certain barriers specifically inhibiting SMEs from development and growth in the sector. 34 of the organisations could be classified as SME's with 19 of the organisations being micro organisations of less than 10 employees.

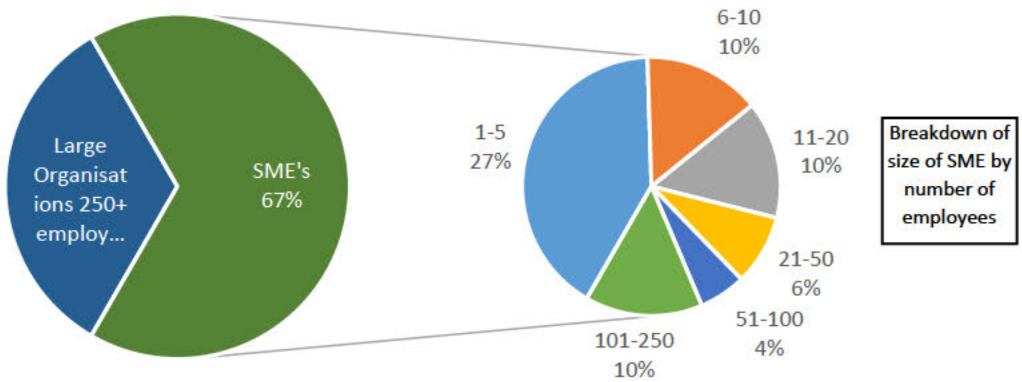

Figure 8.2. Numbers of Employees in responding organisations

Respondents could classify their organisation as operating in multiple sectors – for example as a bio-based, waste, and chemicals company. Of the 51 companies, the most popular classifications were operating the chemicals or energy sectors, Table 8-2 . Ten companies classified themselves as working in 'other' sectors, this included consultancy companies, engineering firms, four R&D organisations and two companies working in carbon capture.

Table 8-2 Sectors in which companies worked

Sector	Chemicals	Minerals/ Construction	Fuels	Metals	Bio-based	Waste	Energy	Other
No. of Companies	20	10	7	5	7	10	20	10

Table 8-3. Technology Readiness Level (TRLs) reported

TRL Range	% of companies reporting activity at the TRL
Research TRL 1-3	45%
Pilot TRL 4-6	33%
Demonstration TRL 6-8	31%
Commercial TRL 9	35%

Table 8-3 gives the range of TRLs that the responding companies operate in. It can be observed that responses covered the complete TRL range although the highest percentage of activity was found in research, perhaps unsurprising as CO/CO_2 utilisation is general viewed as an emerging technology with a strong research based.

40 of the respondents were members of networking and sector organisations such as SPIRE, CEFIC, CO2Chem or other low carbon initiatives. Table 8-4 shows the majority of SME's were members of only 0.94 organisations/network compared to larger companies who, on average, were members of 2.29 organisations/networks (range 0-5 memberships). 11 of the respondents were not part of any low carbon initiatives or programmes.

Table 8-4 Involvement in outside organisations

Organisation/Network/Scheme	Total No. of companies reporting involvement	No. of large companies reporting membership	No of SME's reporting
Spire	7	6	1
Cefic	5	5	0
Eurofer and/or Eurometaux	3	3	0
The European Cement Association	0	0	0
Hydrogen Europe and/or European Hydrogen and Fuel Cell Association	5	4	1
CO2Chem or CO2 Value Europe	26	8	18
German funding programme on CO2 utilisation	4	3	1
KIC's (e.g. Climate, Energy, Raw materials)	8	5	3
BBIC (Bio-based industries consortium	3	2	1
Other CO/CO2 or low carbon related organisations (please specify)	10	3	7
Mean number of memberships	1.41	2.29	0.94
P (Large companies to SMEs)		0.000207	0.000207

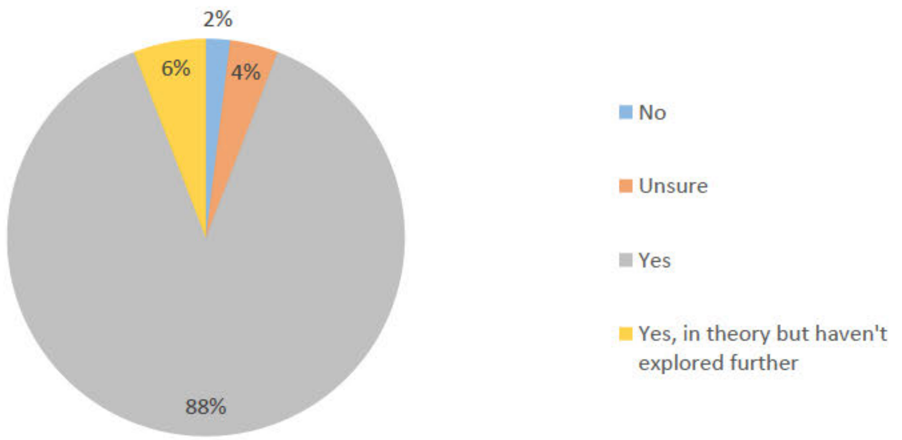

Figure 8.3. Would your organization be interested in options that could allow waste CO_2 or CO to be used to create a value added product?

The respondents were asked if their organisation was interested in options that could allow waste CO_2 or CO to be used to create a value added products (Figure 8.3). 88% of the respondents answered yes, with a further 6% saying they were interested but had not explored options further. One small sized

(<20 employees) R&D consultancy stated that they would not be interested in options to utilise waste CO/CO_2; this response may be due to the respondent interpreting the question to mean would their organisation be interested in actually making products with their own waste CO/CO_2 and as a R&D organisation they do not actually produce products, however no reason for the response is given in the survey.

To establish if the motivation for respondent's interest in alternative carbon technologies was based on their emissions (they wished to utilise their CO/CO_2 emissions to produce products), respondents were asked to state whether they were emitters of CO/CO_2, users of CO/CO_2 or both an emitter and user. The highest percentage of respondents were users of CO/CO_2 (43%) and 23% of companies identified themselves as both and emitter and user (Figure 8.4). Those that identified their organisation as 'other' were often technology or research (R&D) providers who are looking to provide solutions to other organisations and as such did not classify themselves as being 'using CO/CO_2 as a raw material' because although their technology 'uses' CO/CO_2 they themselves do not manufacture and sell a CO/CO_2 based product. Predominately, SME's were users of CO_2 rather than emitters.

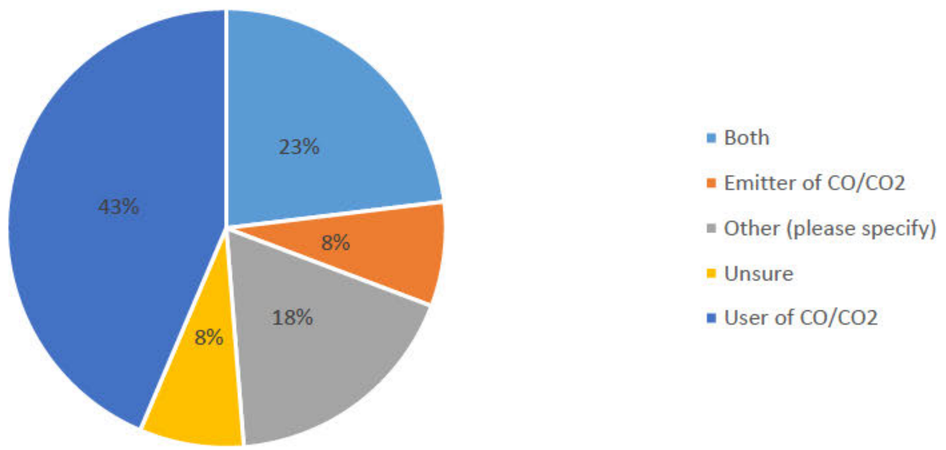

Figure 8.4. Is your organisation an emitter of CO/CO_2 who would like to find utilisation options or do you use CO/CO_2 as a raw material?

8.3.2 Motivation and Knowledge Questions

To assess the reasons why organisations were or may be driven to look for new sources of carbon we asked if the organisation had goals for reducing environmental impacts. 84% responded 'yes' with 6% responding 'no' and 10% 'unsure'. 'Yes' respondents were then asked to select the areas that the environmental goals impacted. Most organisations had multiple goals. Unsurprisingly, 84% of the organisations had goals to decrease their carbon footprint (Figure 8.5). Later in the survey, 12 of the respondents who reported having carbon footprint reduction goals also reported that lack of life cycle analysis (a method of calculating your carbon footprint) knowledge was a barrier to their CO/CO_2

utilisation deployment. The least common environmental goal concerned recycling, with 42% of respondents reporting their organisation had targets in this area.

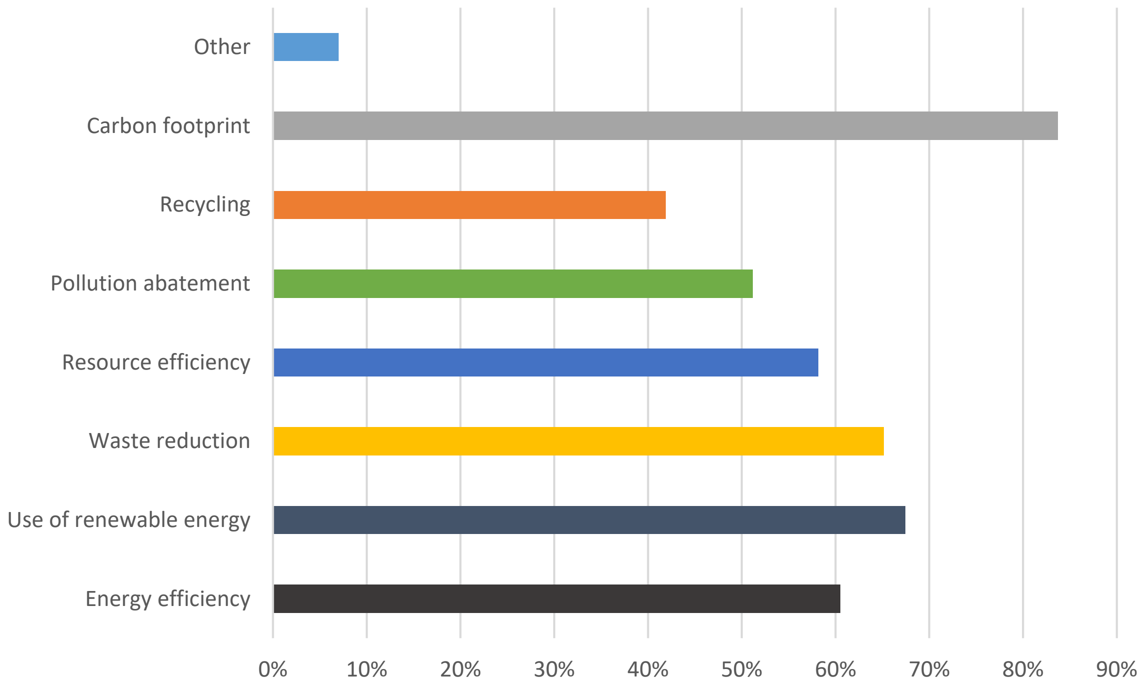

Figure 8.5. Areas in which the respondent's organisation has environmental goals

Respondents were asked to assess their familiarity of CO/CO_2 utilisation in general on 5 point scale 1 (never heard of) to 5 (extremely familiar). 79% of participants responded that they we very familiar with these technologies, with 13% assessing their familiarity as good and 8% as basic (Figure 8.6). No respondents classified their familiarity as vague or never heard. Those reporting a basic familiarly all classified themselves as being in the Energy sector, all reported being interested in alternative sources of carbon however two of the organisations reported that they haven't explored this further. No clear patterns were observable in those rating their familiarity as 'good'; this group contained both emitters and users of CO/CO_2 and covered a range or sectors (chemicals, fuels, energy and metals). Those in the waste, fuels, metals, minerals and bio-based sectors had the highest rating of familiarity with nearly all respondents their familiarity with CO/CO_2 utilisation as 'very familiar'.

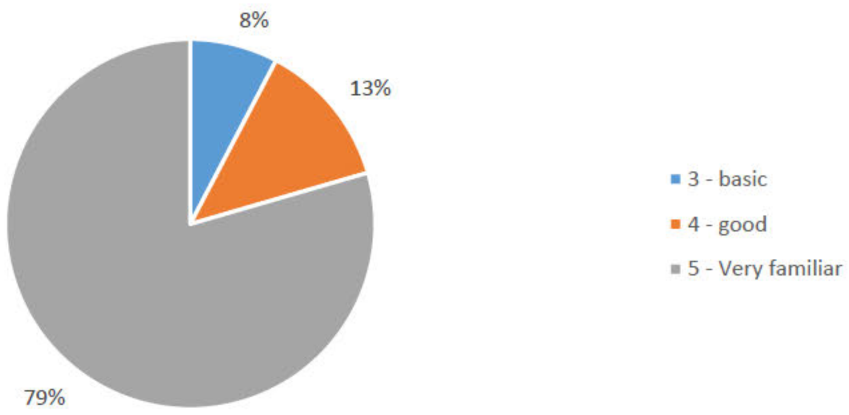

Figure 8.6. Assessment of familiarity of CO/CO_2 utilisation

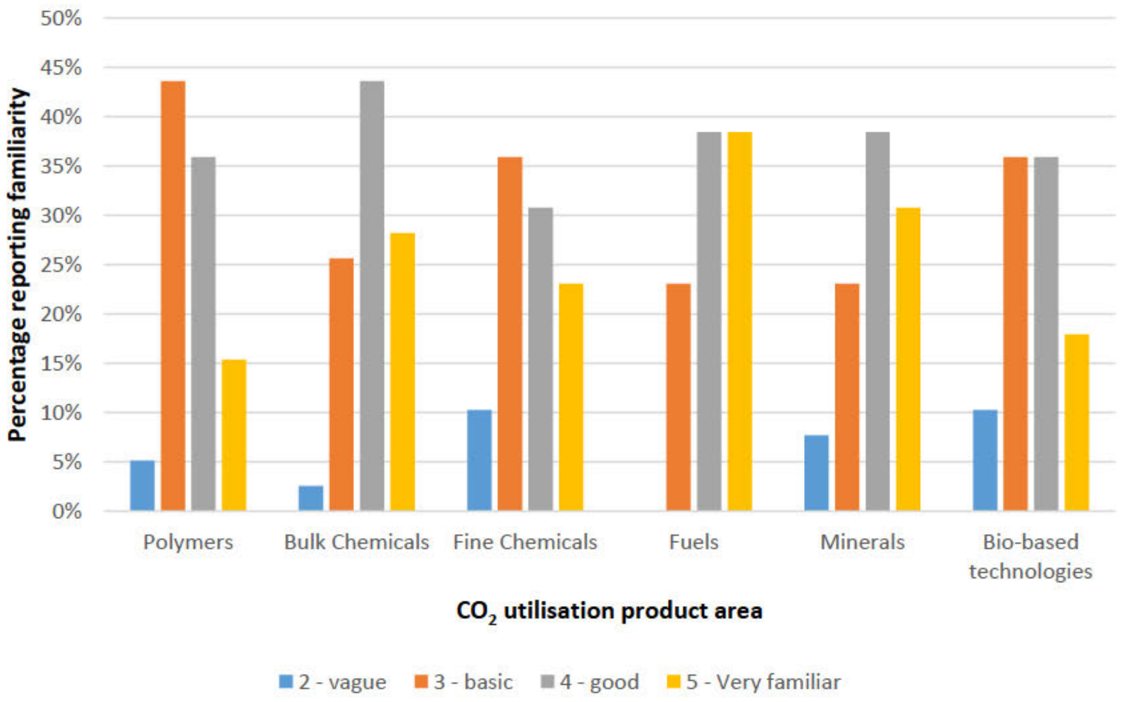

Figure 8.7. On a scale from 1 (never heard of) to 5 (extremely familiar), please rate how familiar you are with these specific CO2 utilization technologies

After general familiarity with CO/CO_2 utilisation was assessed, the respondents were asked to assess their familiarity with different product areas to identify if gaps in knowledge existed in specific areas in specific sectors, Figure 8.7. The mean awareness (Table 8-5) was calculated shows the greatest level of familiarity was with fuel based applications (mean awareness = 4.15), however only 14% of respondents reported that their organisation worked in the fuels sector implying good general awareness of the sector. Least awareness was observed within the polymer, fine chemicals and bio-based products areas, all of which have smaller market potential to use large quantities of CO_2. A one-way ANOVA analysis was performed this shows there was a significant difference in the familiarity of the groups.

Table 8-5 Familiarity of CO_2 utlisation options

Groups	Average	Variance	P value
Polymer production from CO2/CO	3.615	0.664	0.0253
Bulk Chemical production from CO2/CO	3.974	0.657	
Fine Chemical production from CO2/CO	3.667	0.912	
Fuel production from CO2/CO	4.154	0.607	
Mineral production from CO2/CO	3.923	0.862	
CO2/CO bio-based technologies	3.615	0.822	

8.3.3 Questions regarding motivation for alternative carbon sources

In order to assess the motivation for respondent's interest in alternative carbon technologies they were asked to assess the importance of a number of regulator, economic, environmental and business factors (Table 8-6).

Table 8-6. Importance of factors influencing interest in alternative carbon technologies

	Very Important (score 5)	Important (score 4)	Moderately important (score 3)	Low importance (score 2)	Not important (score 1)	Not applicable (score 0)	Mean score
Regulation/taxation	18	12	5	2	2	0	4.077
New business opportunities/ diversification	22	16	1	0	0	0	4.538
Broaden your raw material base	8	9	7	7	4	4	2.949
Using current waste streams	13	15	6	1	2	2	3.769
Public relations/social responsibility	11	13	9	4	1	1	3.667
Reducing carbon footprint	22	9	5	2	0	1	4.231
Making 'greener' products	18	11	9	0	1	0	4.154
Security of supply of raw materials	9	13	4	7	4	2	3.256
Use of excess energy/heat	14	12	3	8	2	0	3.718

The highest mean scores were found to be economically or regulation related (new business opportunities and regulation/taxation) or environmentally related (reducing carbon footprint or making greener products). The issue of regulatory/taxation implications then further explored to ascertain which policies and regulations are having the highest impact. The RED, ETS and Circular economy package showed the highest positive impact over the choice to implement alternative carbon feedstock technologies (Figure 8.8).

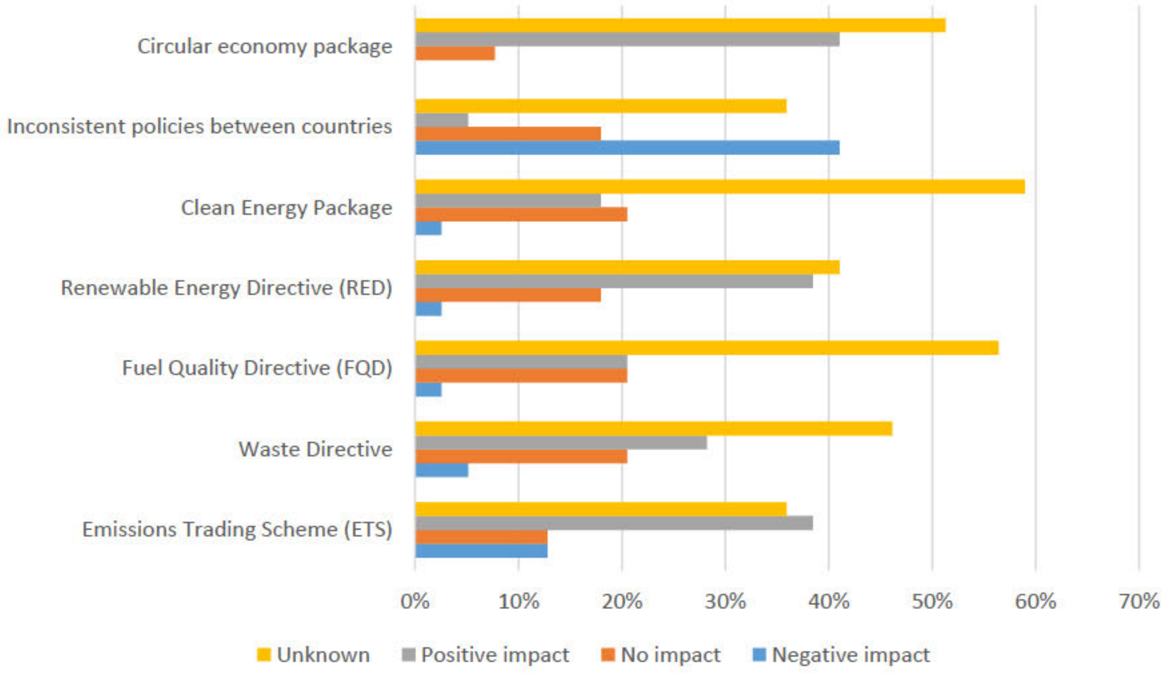

Figure 8.8 Impact of regulations/polices on implementation of alternative carbon feedstocks

8.3.4 Questions regarding inhibiting factors

The SCOT project in its Strategic European Research and Innovation Agenda (Armstrong *et al.*, 2016) identified a number of issues that should be tackled to increase the uptake of CO_2 utilisation. Hence, in this survey, respondents were asked to assess how a number of factors (economic, technical, regulatory) affected the ability of the companies to implement technologies using alternative carbon sources (Figure 8.9) .

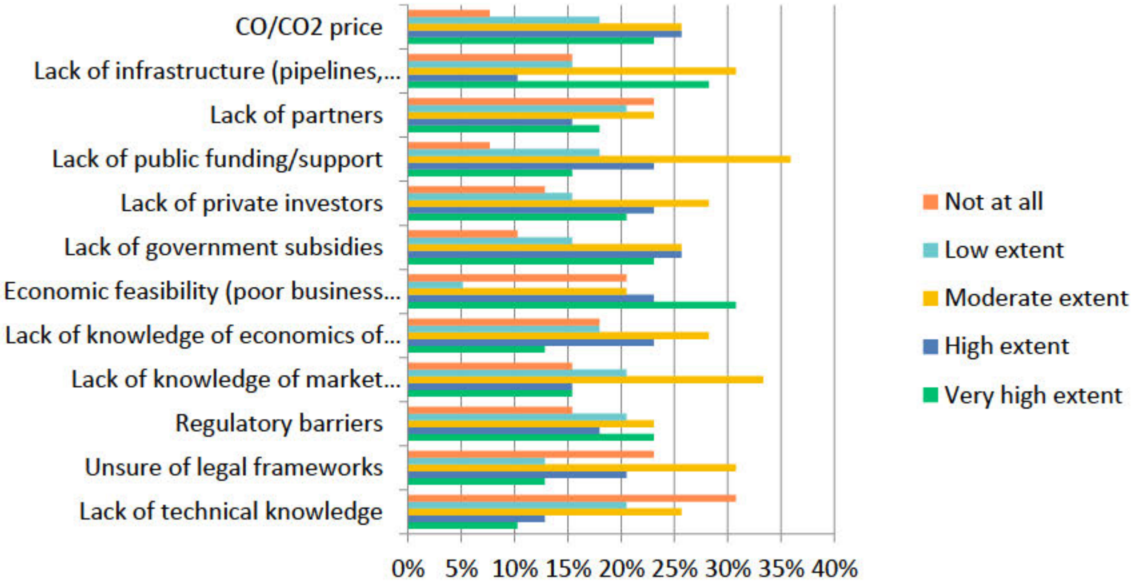

Figure 8.9. To what extent do the following factors prevent your organisation from implementing technologies to use alternative sources of carbon to their full potential?

Table 8-7 Mean score for factors inhibiting technology implementation

	All Mean	Large Company Mean	All SMEs Mean	Micro Mean
Lack of technical knowledge	1.513	1.563	1.478	1.857
Unsure of legal frameworks	1.872	2.375	1.522	1.786
Regulatory barriers	2.128	2.313	2.000	2.286
Lack of knowledge of market opportunities	1.949	2.188	1.783	2.000
Lack of knowledge of economics of the process	1.949	2.250	1.739	2.000
Economic feasibility (poor business case)	2.385	3.250	1.783	2.143
Lack of government subsidies	2.359	2.500	2.261	2.929
Lack of private investors	2.231	2.188	2.261	2.286
Lack of public funding/support	2.205	2.125	2.261	2.500
Lack of partners	1.846	1.688	2.043	2.286
Lack of infrastructure (pipelines, capture facilities etc)	2.205	2.438	2.043	2.071
CO/CO_2 price	2.385	2.125	2.565	2.571

The responses were scored from 5 = very high extent to 0= not at all and the mean value calculated for each inhibiting factor, Table 8-7. The factors with the highest mean value were economic feasibility (poor business case), CO/CO_2 price and lack of government subsidies ; which all are relate to the economic viability of the process. However, mean value for economic feasibility for SME's was much lower, indicating this issue predominantly occurs in larger companies. The issue least affecting implementation is lack of technical knowledge.

Table 8-8 Comparison of inhibiting factors between large companies and SME's

	Large Companies Mean	SMEs Mean	t	P (two tailed)
Lack of technical knowledge	1.563	1.478	0.191	0.849
Unsure of legal frameworks	2.375	1.522	2.033	0.049
Regulatory barriers	2.313	2.000	0.681	0.500
Lack of knowledge of market opportunities	2.188	1.783	0.974	0.336
Lack of knowledge of economics of the process	2.250	1.739	1.218	0.231
Economic feasibility (poor business case)	3.250	1.783	3.403	0.002
Lack of government subsidies	2.500	2.261	0.565	0.575
Lack of private investors	2.188	2.261	-0.170	0.866
Lack of public funding/support	2.125	2.261	-0.358	0.722
Lack of partners	1.688	2.043	-0.782	0.439
Lack of infrastructure (pipelines, capture facilities etc)	2.438	2.043	0.851	0.400
CO/CO2 price	2.125	2.500	-0.921	0.363

Further analysis was conducted to assess whether SMEs had differing factors inhibiting them than larger organisations with greater resource availability by under taking a t-test. Table 8-8 shows the comparison of these between large companies and SME's under the hypothesis that the size of the company effects the impact of a factor. For the majority of factors a significant difference was not note between the responses of large companies and SMEs. However, the issues, 'economic feasibility' and 'unsure of legal frameworks' scored $p<0.05$ and hence the hypothesis is rejected, concluding that in both cases larger companies were more strongly affected by these issues than SME's. Although precise causes for these results cannot be determined, a possible cause of this could be that the respresentatives from SME's answering the survey are specialists in many aspects of their technology area due to the smaller resource pool available within the organisation. Hence, the necessity for the familiarily with legal frameworks and economics. In comparison it is possible those answering from larger companies maybe from be from a research function as CDU is an emerging techology. Therefore, it would not necessily be expected for a research scientist to have significant knowledge of economic or legal framewoks as there are others that would fullfill this role. Regarding economic feasibility, if the larger organisation is needing to move into new technology areas, this would require significant investment hence concerns about economic viability regarding an emerging technologies that have not been significantly proven within the market.

8.3.4.1 Expansion questions regarding barriers

To expand upon the specific technical barriers that are perceived as inhibiting implementation, respondents who indicated that technical knowledge was a barrier were asked to indicate which specific areas are an issue. 27 out of 39 respondents stated that some aspect of technical knowledge was a factor preventing implementation. A one-way ANOVA analysis was performed across all responses, showing there was a highly statistically significant difference in the technical barriers.

Of those that cited technical knowledge as being a barrier, 14 were large companies and 13 SMEs; when compared with the overall sample (of 39, 16 large companies, 23 SMEs) this shows that 89% of large companies cited technical knowledge as an issue compared with 57% of SMEs. Possible causes of this may stem from large companies wishing to diversify into this new technology area and therefore recognising that they do not yet have specific technological knowledge of the field whereas the SME's have specifically chosen the field to work in and therefore have a stronger knowledge base. Figure 8.10 shows the responses to the question 'If technical knowledge is a factor, please assess in which areas you are lacking information'. The overall highest rated issue was 'lack of knowledge regarding scale-up of technologies' with 67% indicating this is an issue. Although a lack of knowledge concerning scale-up affected companies of all sizes, 85% of SMEs reported it as an issue compared to 50% of large companies.

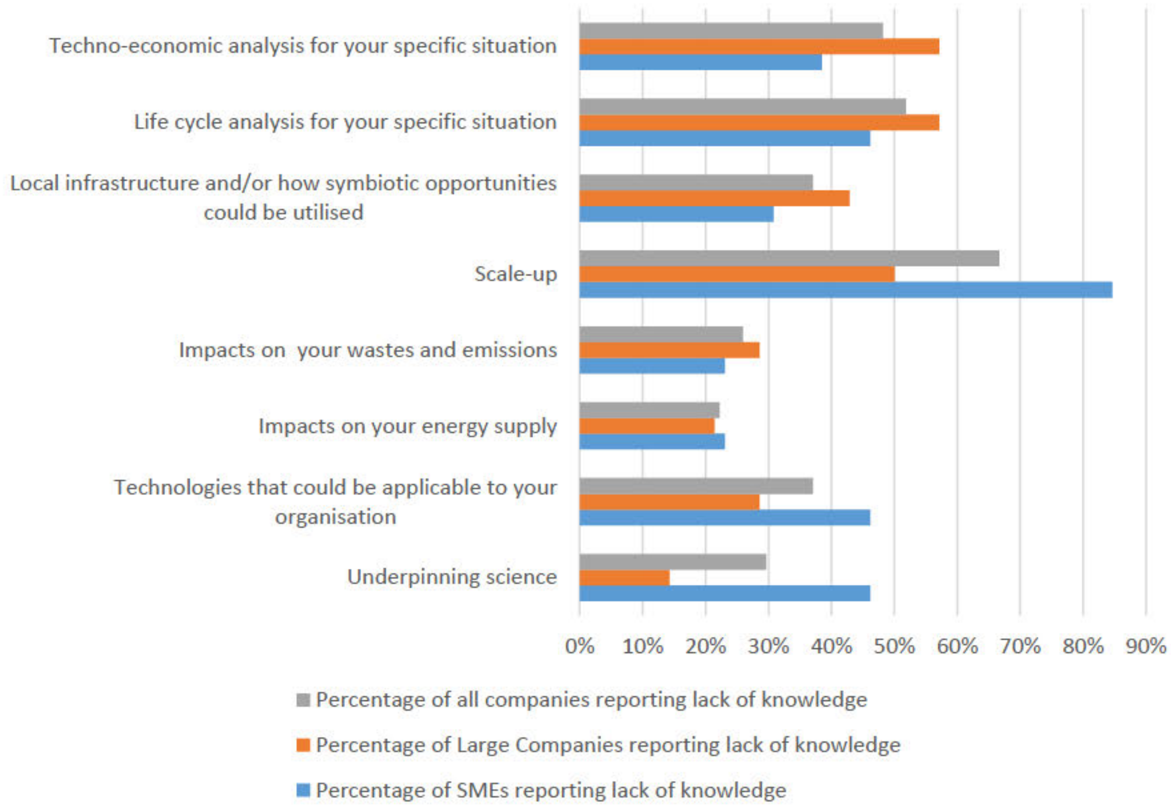

Figure 8.10. Assessment of areas where lack of knowledge is a factor

Finally, the respondents were asked if certain factors could increase their interest in new sources of carbon, with a tick box response. Responses are shown in Figure 8.11 and Table 8-9. A one-way ANOVA analysis was performed across all responses, this shows there was a significant difference in the factors to increase interest.

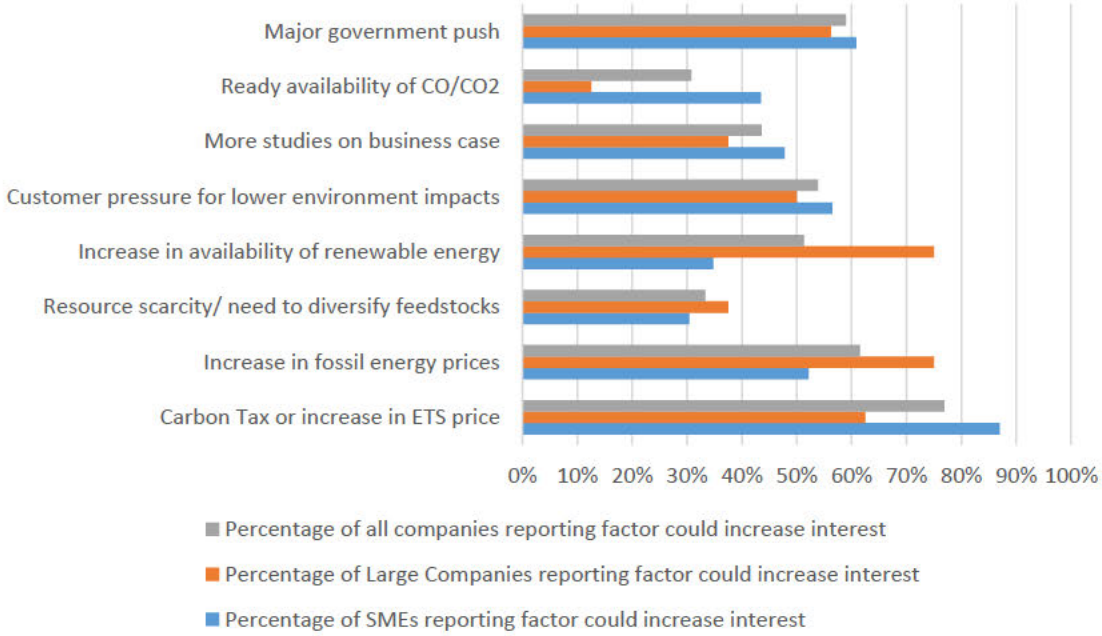

Figure 8.11. Factors that could increase interest in new sources of carbon.

Table 8-9 Analysis of responses for Large Companies and SMEs of factors that could increase interest in new sources of carbon

	Mean	Variance	t	P(T<=t) two-tail
Carbon Tax Large	0.625	0.250	-1.812	0.078
Carbon Tax SME	0.870	0.119		
Fossil energy prices Large	0.750	0.200	1.443	0.158
Fossil energy prices SME	0.522	0.261		
Resource scarcity Large	0.375	0.250	0.450	0.656
Resource scarcity SME	0.304	0.221		
Renewable energy Large	0.750	0.200	2.621	0.013
Renewable energy SME	0.348	0.237		
Customer pressure Large	0.500	0.267	-0.392	0.697
Customer pressure SME	0.565	0.257		
Ready availability of CO/CO_2 Large	0.125	0.117	-2.128	0.040
Ready availability of CO/CO_2 SME	0.435	0.257		
Major government push Large	0.563	0.263	-0.281	0.780
Major government push SME	0.609	0.249		
More studies on business case Large	0.375	0.250	-0.364	0.718
More studies on business case SME	0.435	0.257		

More ready available CO/CO_2 sources and the need to diversify feedstocks or resource scarcity were the least popular options, though more than 30% of respondents stated these would increase interest. For large organisations, 75% stated increasing the availability of renewable energy and increases in fossil energy prices were factors that could increase interest their in new carbon sources. These two factors both concern the energy inputs for the process, indicating that for the larger companies energy source and the realated economics is an important driver in decision making. Comparing responses between large companies and SME's, carbon tax, increase in renewable energy availability and the ready availability of CO_2 resulted significant difference between the two groups.

8.4 Discussion

The aim for this work was to study the barriers to implementation of CO_2 utilisation technologies specifically regarding SMEs. 59% of the respondents reported that their organisations work in more than the country in which they were based. This finding was reflected in all sizes of organisation with 53% micro-enterprises (those with <10 employees), 56% SMEs and 65% of large organisations having operations in more than one country, therefore the size of organisation did not appear to affect where it operated. This is of interest in regard to legislative/regulatory issues, as although EU regulations are applied throughout EU, individual countries can have further regulations which may impact positively or negatively on deployment. This also shows than even within the smallest companies opportunities are seen outside the organisations base country which is positive for growth in the sector.

It can be observed in Fig 8.12 that there slight correlation between the number of employees and the TRL. For micro-enterprises (<20 employees) the split across the TRLs is generally even; though less commercial (TRL9) operations are observed with more operating in pilot (TRL4-6) phase. For large companies a higher level of research (TRL1-3) was observed, this can be accounted for as several R&D specialist organisations responded to the survey and these organisations only operate at low TRL. Although medium sized SMEs (21-250 employees) are a smaller sample size, there were no reported operations at pilot scale, of the 9 companies, 3 reported demonstration and 3 reported commercial operations. Possible reasons for this include moving directly from large scale lab research to small demonstration, by-passing pilot scale or SME's being spun-out from research organisations where the research has previously reached pilot scale before the company is formed.

Figure 8.12 Correlation between size of company and TRL's worked in. Note companies may work in more than one TRL area

The majority of SME's were members of only one organisation/network (mean = 0.94) compared to larger companies who, on average, were members of 2.29 organisations/networks (range 0-5 memberships). 11 of the respondents were not part of any networking or sector organisations. Of these 11, three stated that although they were interested in CO/CO_2 utilisation options but had not explored it further, two were unsure if their organisation would be interested in such options and one stated it would not be interested in CO/CO_2 utilisation. In contrast, all who were members of organisations/networks were interested in CO/CO_2 utilisation options. There is a highly significant difference between the number of outside organisations that large organisations compared to SMEs are part of. Previous research has shown the importance of knowledge transfer (Hoffman *et al.*, 1998; Zeng *et al.*, 2010; Michaelides *et al.*, 2013), therefore it is observed that this is a barrier for CO_2 utilisation and recommended that there should be an drive to encourage SME's within the CO_2 utilisation sector to join further organisations. .

There was an observed significant difference in the familiarity of different products that can be produced from CO_2. The high level of familiarity observed with the production of fuels from CO_2 may be due to the relatively high number of published papers on methanol production from CO_2 (methanol can be used as both a fuel and a chemical feedstock) for example Olah, Goeppert and Prakash, 2009; Goeppert, Czaun, Jones, *et al.*, 2014; Pérez-Fortes, Schöneberger, Boulamanti, *et al.*, 2016; Roh, Frauzem, Nguyen, *et al.*, 2016 and the relative size of the sector in comparison to the other products. Further factors such as the inclusion of CO_2-derived fuels in the EU Renewbable Energy Directive, may also drive awareness within the sector.

Regarding factors influencing interest in alternative carbon technologies, the highest rated factor was 'new business and diversification opportunities that these technologies bring' with 97% of respondents rating this as an important or very important factor and mean score of 4.54, Table 8-6. The environmental aspects, reducing carbon footprint, mean = 4.23 and making 'greener' products, mean = 4.15, are also viewed as being of high importance. The least influential factors were those related to raw materials (broadening raw material base, mean = 2.95, and security of supply, mean = 3.26) indicating that these issues are not currently problematic though this is then counteracted by the desire for the product to be 'green' and hence move away from using fossil carbon. The use of excess energy/heat was of divided importance, those in the fuels sector tended to rate it as an important or very important influence, this was also observed though to a lesser extent, in the energy sectors answers. However, in all other sectors the influence was mixed with responses ranging from very important to not important at all.

As CO_2 utilisation falls within circular economy and sustainability remits, the impact that various regulations and policies have on implementation is of interest. Overall, the Circular Economy package was reported to have the most positive impact, with no negative impacts reported. The issue of inconsistent policies between countries was found to have the most negative impact on the implementation of new alternative carbon feedstocks. This has been recognised anecdotally within the community for some time, often specifically regarding 'end of life' legislations for waste-derived products which can differ from country to country causing issues when trying to establish an existing process in a new country. The ETS is often seen as both a help and hindrance in the CCU sector, and this is reflected with of responses stating it has a negative effect and positive effect. One large company in the chemicals sector stated:

> "*ETS is not consistent with the new energy package"*

whilst a different large chemicals company commented:

> *"Until there is a credible price on carbon or clear legislation most of these technologies will not compete with current technologies."*

For each regulation more than 35% of the responses indicated that respondents (in all sizes of organisation) did not know how regulations/policies have impacted decisions. This rose to more than 50% of responses for the circular economy package, FQD and clean energy package. Comments respondents included:

> "*Not enough knowledge on the content of these packages to know (the impact)"*

and

> "*It is unknown how these regulations may affect our customer's decisions to invest in CCU R&D".*

One SME in the minerals sector summed up their views on the legislative/regulatory impacts in the following statement:

"Using CO_2 as a feedstock is still new. Mineralisation has got advantage about lacking discussions on leakage, storage. And more attention towards "negative CO_2 emissions" is happening. Including these developments into the revised ETS would facilitate the acceptance. In addition to bio-based we need to move to CO_2-based. And consider CO_2 also a re-useable feedstock."

This statement sums up several issues, often CCU is considered as a whole single sector and compared with CCS; this can lead to various problems such as only considering the mitigation aspects of the technology (see Bruhn, Naims and Olfe-Krautlein, 2016 and Artz *et al.*, 2017, for further discussion) and not other additional benefits such as diversifying supply, symbiotic opportunities and the circular economy. Here the respondent highlights mineralisation as this technology is considered carbon sequestration and hence fits policies/regulations designed for large scale CO_2 mitigation/CCS. The understanding of 'negative emissions' is often mistaken, nearly all CO_2 utilisation technologies will emit some CO_2 due to the energy and other inputs needed but often this is not clearly explored through LCA and is not understood by decision makers. Predominantly, the highest level of responses indicated that the effect of that policy/regulations was 'unknown', it can be concluded that further efforts to interpret the impacts of particular regulations/policies for different sectors within the CO/CO_2 utilisation community should be undertaken to ensure organisations are deriving the maximum benefits from these schemes. In an example of this, The SCOT Project explored the issue of the impact of ETS on CDU (see http://www.scotproject.org/content/briefing-paper-eu-ets) concluding that the ETS was only applicable in cases where a mineralised product was produced hence storing the CO_2 for long time periods. In all other cases how the ETS could be applied to CO_2 utilisation is very ambiguous and would rely on careful allocations and life cycle assessment. Further work to clarify how the utilisation of CO/CO_2 is or is not included in the ETS should be undertaken.

Economic factors were observed to have a higher impact on inhibiting technology implementation over regulation or technical barriers. It was found that economic feasibility, CO_2 price and lack of government subsidies had the highest means scores (Table 8-7). However, for different factors the impact varied dependent on the size of organisation (Table 8-8). There was a significant difference ($P=0.002$) between the responses for large organisations and SMEs regarding economic feasibility (poor business case). Possible reasons for this may be the difference in motivation for interest in the CO_2 utilisation sector, for large companies CO_2 utilisation will not be their main business focus but a means for moving to a more sustainable, circularly business model with less environmental impacts, conversely for the SME's this is their main business resulting in the SME's having a strong indication of their own business feasibility. Regarding CO_2 price and government subsidies, there is no significant difference in response between organisation sizes indicating that these are sector wide issues.

Significant differences in the impact of the technical barriers preventing CO_2 implementation were found (P=0.00776). Lack of knowledge about scale-up was the highest rated issue amongst SME's with 11 of 13 organisations reporting it as an issue indicating that SME's particularly struggle in this area. Scale-up of technologies encompasses many factors from engineering to financing, and there is no indication which specific areas of scale up SME's are lacking in knowledge, this should be investigated further in future work. Life Cycle Analysis (LCA) and Techno-economic Analysis (TEA) are the highest rated issues amongst larger companies. This reflects the previous responses regarding lack of knowledge of economics hindering deployment and findings from the SCOT project that identified LCA and TEA as areas that needed particular resource (Wilson *et al.*, 2016). A possible reason that LCA and TEA are particularly identified as problems for large companies is the need for larger companies to assess various different alternative carbon technologies to determine the best fit for their organisation. There is currently a lack of standardisation in the application of TEA and LCA methodologies and a lack of published data resulting in knowledge gaps. This causes specific issues for larger organisations wishing to conduct horizon scanning and screening of technologies to identify best fit options in an economic and timely fashion. SMEs may not encounter this issue, as they only need to conduct their studies on their own specific products or focus areas rather than compare across a wide range of technology options.

When asked what factors would increase interest in CO_2 utilisation, increasing the carbon price within the EU-ETS or introducing a carbon tax was the most popular response with 77% of respondents stating this would increase their interest, Figure 8.11. If the ETS or carbon tax was increased, it is general perceived that this would have a positive benefit on the use of CO_2 as a feedstock due to the desire of emitters to add value to the CO_2. However, this is a 'grey area' (Armstrong *et al.*, 2016) and more clarity on the economic impacts (positive and negative) of increasing ETS or carbon tax is needed. The ready availability of CO/CO_2 was particularly not of interest to large companies and there is a significant difference (P=0.04, P<0.05) between SMEs and large companies. This could be a reflection on the fact that most of the large companies were also CO/CO_2 emitters and therefore are not reliant on external CO/CO_2 supplies.

8.4.1 Further discussion comparing between micro-enterprises, SMEs and larger companies

The data was filtered to analyse trends for differing sized organisations comparing micro-enterprises (<10 employees), SMEs (<250 employees) and large companies (+250 employees). As CO/CO_2 utilisation is an emerging technology there are numerous micro-enterprises trying to bring new technologies to market. By comparing the results between different sized companies, trends could be identified that affect companies at different stages and between those (usually large companies) who are diversifying into the field and those whose primary business is in the field. Notable trends included the following:

- 32% of micro-enterprises and 47% of SMEs had projects either at demonstration or commercial scale, compared with 65% of large companies. It is encouraging that nearly 50% of SMEs have technology at this scale as often SME's struggle to overcome the 'Valley of Death' in moving technologies from pilot to demonstration scale, though scale-up issues or lack of investment.
- Most of the SMEs were part of the CO2Chem network (free to join) or CO2Value Europe (membership fee) but only 6 out of the 34 were part of any other networks or groups. Large companies had a much more varied membership with 65% of the companies being members of more than one external organisation/network. Only 1 larger SME was a member of CEFIC or SPIRE, this is not unexpected as membership of CEFIC is geared towards large organisations; though it was unexpected to discover that the SME's were not greatly participating in other knowledge transfer networks such as KICs or other relevant associations.
- 71% of micro-enterprises reported a lack of technical knowledge regarding scale up of technologies was an inhibiting factor to deploying technologies. However, only one further SME (size 11-20 employees) reported lack of knowledge of scale up as an issue; indicating that this is a problem specifically affecting the smallest sized SMEs.
- 87% of SMEs and 86% of micro-enterprises report that an increase in carbon price or ETS would increase interest in alternative carbon technologies. There is a significant difference between the results for SMEs and large companies, showing that carbon prices are perceived to have a higher impact on increasing interest in smaller organisations. This may be due to the proportionally higher financial benefits that carbon taxes could have on the income of the SMEs.
- Large companies reported a higher level of lack of information for technical knowledge related to LCA and TEA (63% of respondents) compared to SMEs (35%). This may be due to large companies looking to invest in alternative carbon technologies and so wishing to assess multiple opportunities and therefore using LCA and TEA as a method to do this whereas SME's are likely to have conducted LCA and TEA on their own technologies at a developmental stage. In general, there is a lack of publically available LCA and TEA on comparisons between

alternative carbon technologies (Artz *et al.*, 2017), therefore it is expected that large companies would report a higher lack of information than SMEs.

8.5 Conclusions and Recommendations

Although the survey is limited in size due to the small size of the sector sampled, a number of conclusions can be drawn from the responses. The study aimed to identify barriers for CO_2 utilisation SMEs and to determine if issues previously highlighted in literature e.g. policy/regulation, LCA studies, financial knowledge, and external links also affected SME's in the CO_2 utilisation sector. It was observed that these issues did affect CO_2 utilisation SME's to some extent. Significant barriers for SME's were found to be regulation, lack of funding/subsidies from government, investment and public funds, lack of partners and the CO_2 price. More than 40% of SME's reported lack of knowledge as an inhibiting factor in the following areas: LCA, scale-up, applicable technologies and underpinning science; with lack of knowledge in scale-up effecting more than 80% of respondents. There were some differences in barriers between SME's and Larger companies with larger companies reporting they were less sure of legal frameworks and lack of economic feasibility. Areas barriers regarding funding, technical knowledge, infrastructure and CO_2 price were equally reported.

Many of these barriers can be tackled with knowledge transfer or funding initiatives. The results from the survey can be drawn together into a number of practical recommendations to benefit the sector and work towards removing barriers.

Barrier 1: Knowledge of Policy and Regulation

There is an observed lack of knowledge of how various policies and regulations have impacted decisions to implement alternative carbon feedstocks. This finding echoes a recommendation from the SCOT Joint Action Plan (Wilson *et al.*, 2016), where it is recommended that policy assessment is undertaken to increase deployment of CO_2 utilisation technologies. 47% of the responses gave 'unknown' as the impact of different policies or regulations on the organisations decision to implement alternative carbon technologies. No difference in knowledge of the impacts of policies/regulations was observed between SMEs and large companies indicating that it is a sector wide issue. In particular, increasing the ETS/carbon tax was perceived as having a positive impact on future decisions to engage with alternative carbon technologies, however the SCOT project has highlighted a number of 'grey areas' within the ETS regarding the inclusion of CO_2 utilisation technologies and confirmed that clarity is needed to understand possible implications for the deployment of CO_2 utilisation.

Recommendation: It is recommended that organisations wishing to implement CO_2 utilisation technologies and CO_2 uitilisation-based associations undertake comprehensive policy assessment of all *relevant policies/legislation as a priority. Subsequently, conclusions should be as widely distributed as possible through organisations/networks to ensure knowledge transfer.*

Barrier 2: Knowledge transfer

In general, it was found that most SMEs are members of only one external organisations or network. There may be a number of reasons for this including capacity/time and cost of joining. Therefore, opportunities for knowledge transfer may be limited and hindering deployment of new technologies. This may particularly occur in knowledge transfer between SMEs and larger companies, and can be observed in the responses of larger companies stating they were lacking information on the LCA and TEA of alternative carbon processes which the SME's have as innovators. It is recommended that work is undertaken to improve knowledge transfer in the sector, particularly engaging SMEs in multiple programmes to ensure information flow is not reliant on solely one source which could lead to gaps in knowledge transfer and missed cross-fertilization opportunities. Of the companies that were not members of any network or external organisation, a higher rate of uncertainty around their organisation's interest in alternative carbon sources is observed, indicating that involvement in external organisations is directly correlated to interest in alternative carbon technologies.

Recommendation: SMEs should be encouraged to partake in active membership in external organisations with a knowledge transfer focus to improve engagement in alternative carbon technologies as a whole. Knowledge transfer organisations should target CO2 utilisation SME's to encourage membership especially those organisations with free/low cost membership which would remove financial barriers.

Barrier 3: Factors effecting the chemical sector

The chemicals sector respondents appear to be the most positive to the deployment of new carbon technologies, with all companies rating new business opportunities as important or very important. This is encouraging as the chemical sector responses have generally rated their knowledge of CO_2 utilisation as 'very familiar', with 45% of the companies saying they did not lack the technical knowledge to implement new carbon technologies. The chemical sector respondees rate inconsistent policies between countries as a having a highly negative effect on implementing new technologies and would like to see a higher carbon tax/ETS and a major governmental policy push to increase interest. Therefore, it can be concluded that due to the high levels of knowledge that already exist in the chemicals sector, the major barriers to deployment are economic and policy related; which could be eased by implementing an incentive mechanism.

Recommendation: Investigate and initiate incentive mechanisms for the chemical industry to deploy alternative carbon technologies including new governmental policy and economic incentives.

Barrier 4: Funding in SMEs

Differences were observed between micro-enterprises and SME's, particularly regarding scale-up of technologies. Here access to knowledge transfer opportunities and partnerships with universities to utilise external skills-sets may be useful to bridge the knowledge gap. It was encouraging to observe that 32% of micro-enterprises had demonstration or commercial scale projects, indicating that nearly a third had overcome scale-up barriers. Funding programmes for SMEs directed at this development stage (TRL5-8) would enable technology deployment to be expedited. New SME funding programmes that necessitate that TEA and LCA studies are published (within the bounds of commercial confidentiality) could also be particularly beneficial to larger organisations wishing to make decisions about which new technology solutions to invest in.

Recommendation: Initiate a funding mechanism for SMEs relating to TRL5-8, this should include a requirement to publish LCA & TEA (within the bounds of commercial confidentiality).

Barrier 5: Familiarity with technology options in core feedstocks

The highest level of familiarity was found to be with the production of fuels from CO/CO_2, although only 14% of respondents reported their organisation worked in this sector. This may be due to the relatively higher levels of research in this area compared with other sectors, or could be a result of companies investigating diversifying into a new market/sector but yet to have made the transition. Lower levels of familiarity were observed in the production of fine and bulk chemicals indicating that if alternative sources of carbon are to be introduced in these areas a greater level of knowledge and investment is required. Implementing research targets to particularly focus on core feedstocks for the process industry could address this issue.

Recommendation: Increase research and knowledge regarding the opportunities to produce core chemical feedstocks for the process industry via research targets and increased funding in FP9 and other mechanisms.

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9 Communication regarding CO_2 Utilisation

The work contained in this chapter was part of the Horizon 2020 CarbonNext project, SPIRE5; GA no: 723678 [1] and subsequently published as a chapter in Carbon Dioxide Utilization: From Fundamentals to Production Processes (North *et al.*, 2019). Katy Armstrong was the sole author of the work.

Communication of CO_2 utilisation technologies to external stakeholders is key to ensure optimal uptake of technologies and hence for its potential to be realised. However, complexities in communicating CO_2 utilisation effectively have arisen and the same communication strategy cannot be employed for diverse stakeholder groups. Based on initial work by the author in Jones *et al.*, (2014) and Jones, Olfe-Kräutlein, Naims, *et al.*, (2017) and subsequent other studies into the perception of CO_2 utilisation, herewith a set of principles for the communication of CO_2 utilisation are derived and presented. It is recommended that when communicating about new CO_2 utilisation products the interests and motivations of the stakeholders are carefully considered from the start. Furthermore, there are identified a range of considerations and misconceptions that should be taken into account when deciding on communication strategies for CO_2 utilisation.

This chapter has been removed by the author of this thesis for copyright reasons

North, M. and Styring, P. (eds) (2019) *Carbon Dioxide Utilization: From Fundamentals to Production Processes*. De Gruyter.

[1] www.carbonnext.eu

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10 Public Perception, Acceptance and Education of CO_2 Utilisation

In this chapter the potential acceptance for CO_2 utilisation technologies by the public is explored. The adoption of new technologies depends on many aspects, including the willingness of the public to accept and therefore adopt the technology. This can be complicated when the technology itself is complex combining many facets for successful deployment. Chapter 9 explored communication of the potential of and the science behind CO_2 utilisation with a variety of stakeholders. This chapter discusses and extends the work on public acceptance published by the author in (C.R. Jones *et al.*, (2014) and Jones, Olfe-Kräutlein, Naims, *et al.*, (2017). The papers are included in the Supplementary Material section of the work for the reader's convenience. In this chapter the acceptance of the public is explored through two novel approaches to communicating CO_2 utilisation, the use of Top Trumps and the development of an interactive App. The first public perception studies confirmed general positive attitudes towards CO_2 utilisation but highlighted the complexities of communicating the subject with participants reporting very low initial awareness of CO_2 utilisation. However, after engaging with the focus group and guided discussion indicated preferences to CO_2 utilisation over CCS and could see the value in creating products from CO_2. Similarly, the participants utilising the App also reported low prior knowledge, but primarily ranked their learning from using the App as high or very high. The App was rated highly within the focus groups for ease of use, learning and enjoyment, confirming it as fit for purpose as a tool to communicate CO_2 utilisation opportunities. Therefore, it can be concluded that the app was successful in communicating the complexity of the topic in an engaging self-guided manner.

Research publications below arrising from this chapter can be found in the Supplementary Material:

Jones, C.R., Radford, R. L., **Armstrong, K.** and Styring, P. (2014) 'What a waste! Assessing public perceptions of Carbon Dioxide Utilisation technology', *Journal of CO2 Utilization*, 7. doi: 10.1016/j.jcou.2014.05.001.

Jones, C. R., Olfe-Kräutlein, B., Naims, H. and **Armstrong, K.** (2017) 'The Social Acceptance of Carbon Dioxide Utilisation: A Review and Research Agenda', *Frontiers in Energy Research*, 5. doi: 10.3389/fenrg.2017.00011.

10.1 Introduction

CO_2 utilisation is a broadly used term to describe the use of CO_2 as a carbon source to produce a wide range of products from fuels to pharmaceuticals, plastics to building blocks. Although the aim of CO_2 utilisation can simply be distilled into 'replacing fossil carbon with carbon from carbon dioxide', complexities lie in how to convey the interactions between CO_2 utilisation, renewable energy, resource efficiency, economic and environmental impacts to stakeholders. Thus, describing the place of CO_2 utilisation in a circular, sustainable economy to general public is not necessarily easy, as discussed in Chapter 9; due to the wide variation of processes, products and motivations involved.

Assessing public opinions and gaining public support has been found to be necessary in any technology development (Apt *et al.*, 2006 also see Chapter 9). Consumers can be cautious of and even resist novel technologies and innovation (Ram *et al.*, 1989). Functional and psychological barriers preventing adoption can exist and strategies to overcome these are necessary. Within sectors closely linked to CO_2 utilisation (such as renewable energy and CCS), research has highlighted that often assessing public opinions is be considered too late in the development cycle, hence causing confusion and scepticism over technologies (Apt *et al.*, 2006; Parkhill *et al.*, 2013). Therefore, it is prudent that greater effort is needed to engage with stakeholder groups and understand perceptions.

Within CCS, public perception studies have concluded that limited research exists to determine opinions especially in the wider community. (Apt *et al.*, 2006; Ashworth *et al.*, 2009; Bradbury *et al.*, 2009; Shackley *et al.*, 2009; Pietzner *et al.*, 2011). Terwel *et al.*, (2011) concluded that public (market) trust in CCS stakeholders is key to acceptance. Wüstenhagen *et al.*, (2007) identified that acceptance could be viewed in three dimensions: socio-political acceptance, community acceptance and market place acceptance, Figure 10.1. Within this triangle each dimension is interconnected with one dimension having effect on another. In Jones et al., (2017, see Supplymentary material) we examined the application of Wüstenhagen's triangle to CDU; concluding that there is a lack of systematic research in this area and hence setting out a research agenda. The lack of public awareness of CO_2 utilisation technologies identified in the few studies into the perceptions of CDU is furthermore considered. Jones et al, observed that within exisiting works CDU is primarily framed in a climate chage context with other aspects and interactions not expounded. Attention is drawn to the benefits of enhanced communication activities to identify misconceptions and scientific understanding to customers for CO_2-derived products.

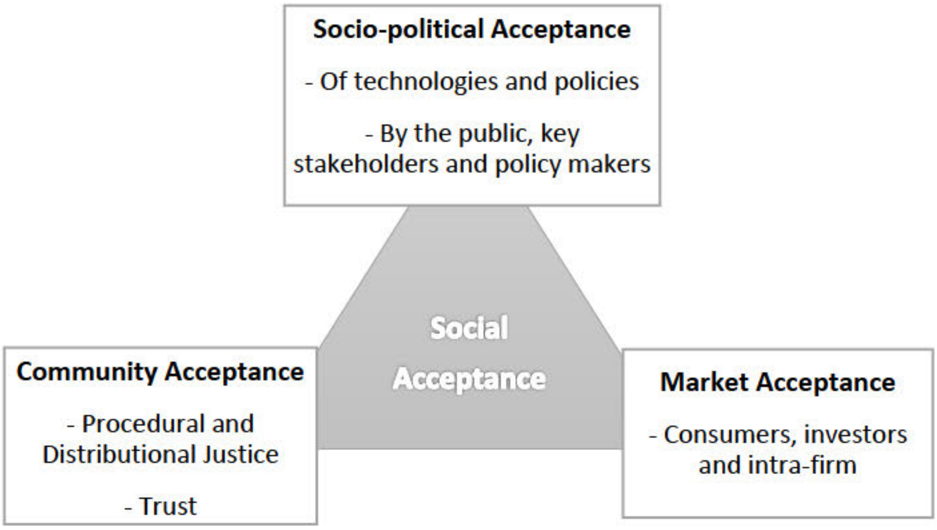

Figure 10.1 Three dimensions of social acceptance adapted from Wustenhagen et al (2007)

The public understanding of science has long been of interest and concern with many proposed approaches to increase knowledge through education and public engagement activities (The Royal Society, 1985; Miller, 2001). In the field of sustainability, education is deemed necessary to increase the public's understanding of sustainability issues (Bangay *et al.*, 2010). Stern (2007) noted that educating children in school on climate change and creating a shared understanding of the issues was key to changing behaviours and policy. Bangay *et al.* state that educational responses to climate change and sustainability need to go further than simple prescribed curriculum content and children need to be empowered and equipped to deal with the changes which will occur. To achieve this varied forms of delivery will be need including formal and non-formal approaches. Climate change, sustainability and the circular economy are complex topics with many facets. New approaches to combat these issues are continuously being researched and deployed, therefore there is a wealth of information available. Computers or tablets can offer easy access to complex, evolving learning material. Within the UK population, 92% of children aged 12 stated they had access to a laptop or computer in a YouGov 2019 poll (*Four in ten British kids has their own tablet by age six | YouGov*, 2019) confirming this is an accessible way for information to be delivered. However, the challenge is to deliver this information in an appropriate method to encourage engagement and learning.

Apps are software applications designed to run on computers or mobile devices including tablets. Apps can take many forms including games and simulations. Within education, they can be used to enhance learning outcomes, to present and allow access to information in new ways by providing an interactive, enriched learning experience (Ellis, 1984; Castek *et al.*, 2013; Dicheva *et al.*, 2015). Apps can allow users to engage in active, meaningful, social learning by utilising known learning processes

(Hirsh-Pasek *et al.*, 2015). Two approaches can be used when introducing games to learning, Serious Games and Gamification. Serious Games do not have an entertainment purpose and are designed for a specific purpose or learning goal (Corti, 2006). Serious Games often focus on building specific skills or enabling the user to experience specific situations in which they can role play, for example a flight simulator. Serious Games can allow the user repeatability until they are confident in their learning and outcome in the situation (Hauge *et al.*, 2012). Deterding *et al.*, (2011) defines gamification "*as the use of game design elements in non-game contexts"*. Gamification does not aim to necessarily produce a fully-fledged entertaining game, but looks to incorporate some elements such as limited resources, leader-boards, challenges, playtesting, time constraints or goals into the applications or simulation which would normal have a non-game context. In gamification, game design elements have been used to motivate users learning and engagement in a wide variety of fields such a finance, health and sustainability (King *et al.*, 2013; Peham *et al.*, 2014; Huber *et al.*, 2015; Seaborn *et al.*, 2015; Patlakas *et al.*, 2017; Becker *et al.*, 2019; Capellán-Pérez *et al.*, 2019). The use of game elements within an app facilitates decision making and enhances problem solving skills combining more formal (school) and informal learning possibilities (Admiraal *et al.*, 2007). Admiraal *et al*, define key characteristics of game based learning for users as including allowing users to feel empowered, creating new challenges which are 'pleasantly frustrating', providing information on demand or just when it is needed rather than an information overload and providing opportunities to see how the problem fits into a larger meaningful system whilst the simulated reality removes danger and risk of not solving the problem in 'real-life' (i.e. failing to achieve the required aim). Simulations and games can allow complex real world scenarios to be conveyed and abstract concepts explored in ways that may not be otherwise possible due to limitations of safety, resource or practicality (Ellis, 1984). Furthermore, the use of serious games or gamification methods within sustainability education have been demonstrated to create awareness and support learning (Seaborn *et al.*, 2015; Gatti *et al.*, 2019; Scurati *et al.*, 2020).

A comprehensive review of gamification in science education from 2012 to 2020 was carried out by Kalogiannakis *et al.*, (2021). The review identified positive learning outcomes including higher academic marks when students achieve higher game scores, higher levels of motivation for learning, enhanced understanding of concepts and improved problem-solving skills. Some negative aspects were found including inadequate computer skills inhibited progress, unequal learning outcomes between sexes and some students too focused on the game which hindered learning. However, the study concluded that there is a strong correlation between improved motivation and significant learning results when utilising a gamification approach.

10.2 First steps into exploring public awareness of CO_2 utilisation

First steps towards exploring the public awareness of CO_2 utilisation were undertaken in 2013. A collaboration between the Department of Psychology and the author at the University of Sheffield undertook the first systematic studies into this area (see Supplymentary Material for Jones *et al.*, 2014 then subsequent work in Jones *et al.*, 2015, 2017). Whilst the psychology department provided the experience for the information choice questionnaire design, the author provided the expertise on the carbon dioxide technologies. CDU technologies are recognised as unfamiliar to the general public. Therefore, it was established that the participants would need to be provided with background information regarding CDU to enable them to make informed decisions. Presented data would need to be quick to understand, accessible to those with no knowledge in the area and to be in enough depth to allow choices to be made between technologies by participants. After consideration of approaches, a short video and a set of 'top trumps' cards were designed to communicate to the background information on five CDU processes plus CCS by the author. These were then used on multiple occasions for public perception research to test this novel approach of increasing knowledge of CDU.

Top Trumps[1] is a card game which presents numerical data relating to numerous categories in which the players compare scores to try and 'trump' each other (win by having the highest score in the specified category). For this research, participants were not playing the game against each other but could use the categories to compare different aspects of one technology with another. It was theorised that a Top Trumps approach would provide the participants with sufficient data in a simple visual format which was quick to comprehend. Technologies were rated on a scale of 0-10 for investment payback time, market potential, carbon reduction, cost benefit to consumer, business as usual (Table 10-1). Commercial availability was also given as a measure in years, how long it will be before this technology is available for commercial use. Following each score, a short description was given to help the participants understand why the score was assigned, Figure 10.2. Scores were assigned for each of the five CDU products (methanol, cement, plastics, transport fuel, enhanced oil recovery (EOR)) and CCS. Scores were then verified by a group of 10 academic experts from the CO2Chem network.

[1] https://toptrumps.com/about/

Table 10-1 Criteria for Top Trumps cards created by K.Armstrong published in Jones *et al.*, (2014)

Criteria	Description
Investment payback time	How long it will take the money invested in the storage process or the new technology to be paid back. The lower the rating, the longer it will take and so the less economically efficient it is.
Market potential	Whether the product produced by the captured CO_2 will have the potential to sell. The higher the rating the more potential it has.
Carbon reduction	Refers to how much carbon is actually being taken out the atmosphere or used to produce another product. The higher the rating, the more carbon that is removed and therefore the more effective it is.
Safety	Indication of the risk towards health and safety of implementing the technology.
Cost benefit to consumer	Refers to whether the price of capturing the CO_2 or transforming it into another product will cost the customer through increased energy prices or whether the profits from the end product will offset this cost. A higher rating means that the technology is less likely to make energy prices increase.
Business as usual	Refers to the extent to which the option will enable/disrupt the current ways in which business and society operate; how much 'business' will remain as usual. For example, are we still able to live our day lives and use transport to the same extent. A higher rating suggests business as usual is more achievable.

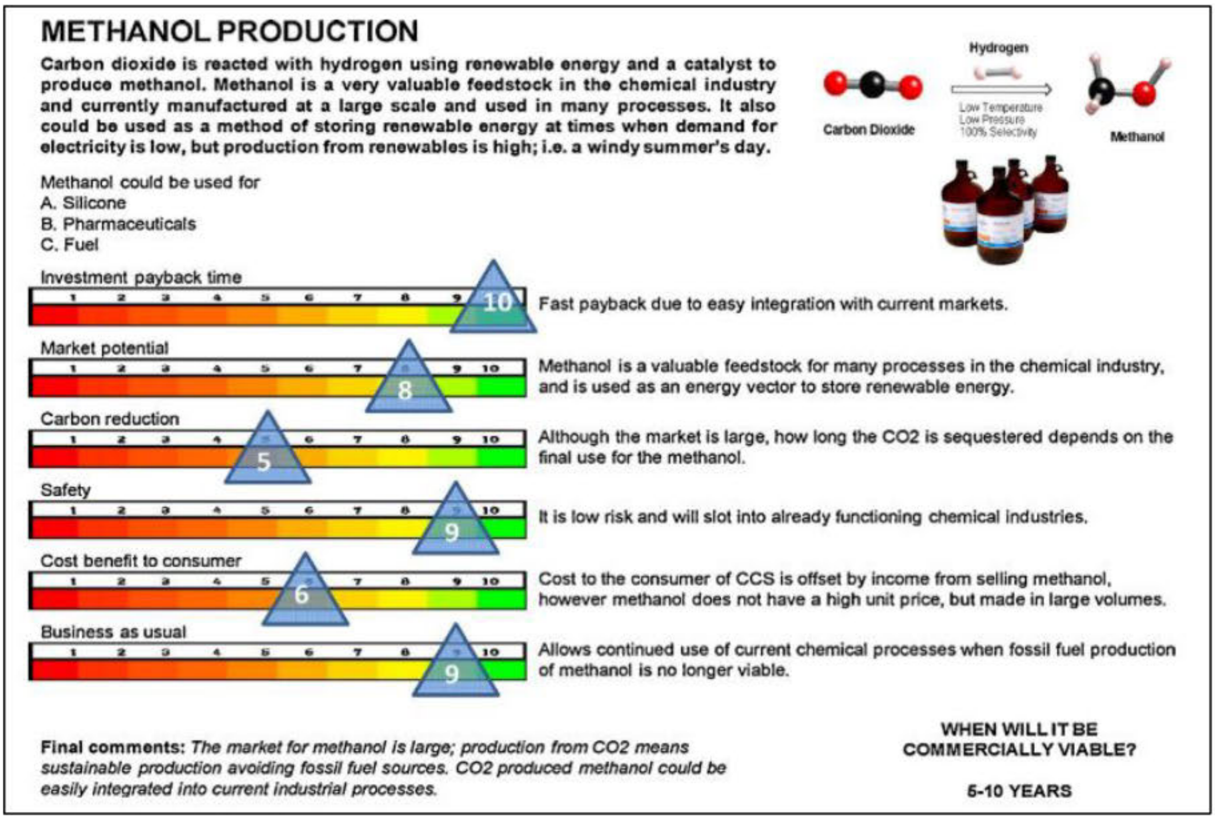

Figure 10.2 Example CDU Top Trump Card created by K.Armstrong published in Jones *et al.*, (2014)

Participants in the initial research were found to have very low awareness of CDU technologies and found the information provided for the study in the Top Trumps cards to be "moderately largely unbiased, trustworthy, credible, sufficient and understandable" (Jones et al., 2014). It was also noted that the participants indicated that they considered all information provided but primarily considered 'carbon-reduction potential' when making decisions indicating that CO_2 emissions were a key priority. Participants attitude certainty towards CDU was found to increase as a result of participating in the survey; however, their attitudes to CDU did not become any more or less favourable. This is interesting as it indicates that, in line with the stated strengths of ICQ (information choice questionnaire) designs, people felt more knowledgeable about CDU after participation and hence are likely to base their opinions on more stable (and directive) attitudes.

Lessons learnt during these early experiences with complexity of communicating CDU technologies to allow individuals to make informed choices or decisions and hence to increase CDU acceptance lead to the creation of a research agenda (see Appendix for Jones, Olfe-Kräutlein, Naims, *et al.*, 2017). Here it was concluded that whilst perceptions amongst stakeholders will shape future pathways, research into social acceptance of CDU is limited and needs to expand to explore views of the broad, diverse range of stakeholder groups involved.

10.3 CO2GO

As noted in the public acceptance research described above, it is recognised the lack of prior knowledge of CO_2 utilisation is hindrance to the creation of informed opinions and acceptance. Therefore, introducing new methods to communicate CO_2 utilisation to wider audiences is of benefit. Gamification has been found to engage and educate stakeholders (King *et al.*, 2013; Peham *et al.*, 2014; Huber *et al.*, 2015; Seaborn *et al.*, 2015; Patlakas *et al.*, 2017; Becker *et al.*, 2019; Capellán-Pérez *et al.*, 2019) and is particularly attractive and accessible for younger audiences familiar with technology. A benefit of using gamification is the ability for complex topics, such as CO_2 utilisation, to be investigated by enabling interactive exploration of options. Thus concept of gamification was employed to create the CO2Go App in 2015/16. With the intention of enabling users to explore choices involved in creating CO_2-derived products and their associated emissions. The app was developed as part of the EU FP7 CyclicCO2R project (http://www.cyclicco2r.eu)

The concept for the App built on the learning from the initial public perception work of Jones, Armstrong, Styring and Radford (2014) and the creation of 'top trumps' cards by enhancing the method of comparing technologies via applying a digital, interactive, gamification approach. Some similar CDU technologies were included; though in CO2Go, CCS and EOR were excluded due to the focus on creating new products from carbon sourced from CO_2. The App goal was to interactively illustrate how CO_2 could be useful instead of being perceived simply as waste and an environmentally harmful product. The target audience for the App was secondary school age children (11-16 years). It was felt that aiming the App at this age would ensure that it was accessible to all with a basic high school science education, thus enabling the App to suit the widest possible audience.

10.3.1 App Content

Recognising the low levels of pre-knowledge of CO_2 utilisation previously identified, a simple introduction to communicate the idea of utilising CO_2 was created. The five screen introduction (Figure 10.3 Introduction to CO2Go) focuses on the properties of CO_2, how it is used, the carbon cycle, the role of CO_2 in global warming finishing with posing the question of can we use CO_2 like nature to make products we need and in doing so reduce CO_2 emissions? Gameplay within the App then enables the user to explore how making different products using different CO_2, electricity and hydrogen sources can effect CO_2 emissions in the EU.

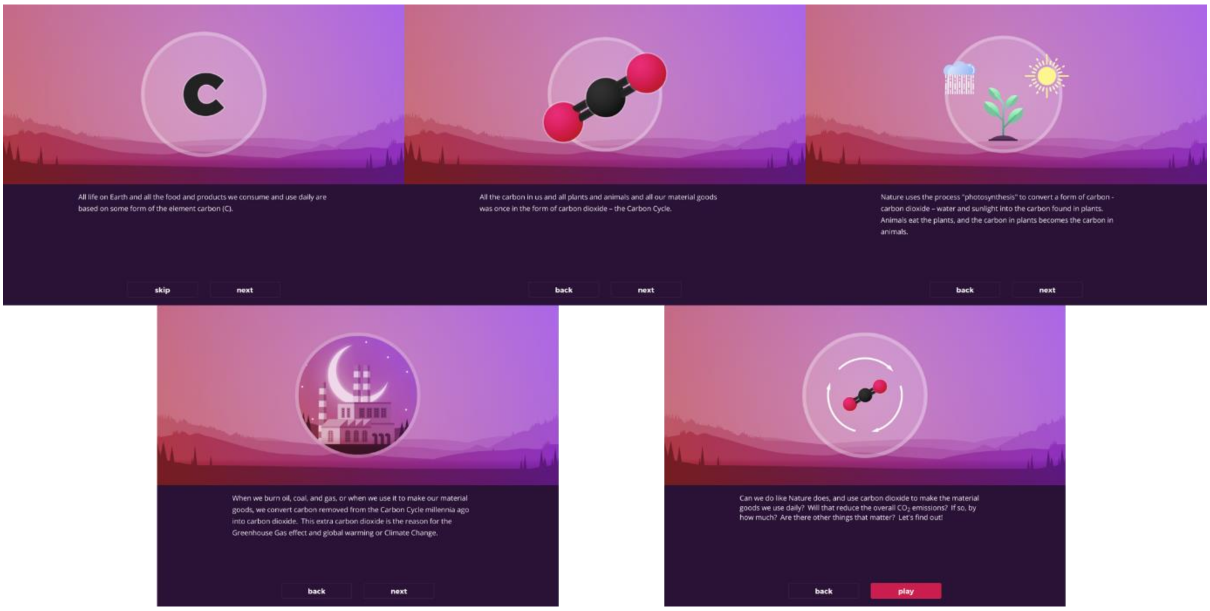

Figure 10.3 Introduction to CO2Go

Decision-making within the App was split into different variables. Thus, enabling the user to choose the country in which to production occurs, the products made, the amount of product, the source of CO_2, the source of hydrogen and the source of energy. All variables can be altered at any point to allow the user to compare results when for example switching country but leaving all other variables the same or by switching from the grid energy mix to wind power.

As the App was created as part of an EU funded project, six European countries with differing energy mixes were included: the UK, the Netherlands, Germany, Denmark, France and Spain. Energy generation in each country emits differing amounts of CO_2 dependent on the makeup of the grid mix. For example, at the time the App was made, France generated over 75 % of their electricity from nuclear power, Denmark generated 40 % from wind energy and 16 % from biomass. The Netherlands generated nearly half their electricity from gas, while Spain had an evenly distributed energy profile without one clear dominating source of electricity. The electricity data were based on 2014 values of the electricity grid mix, taken from http://www.carbon-calculator.org.uk/ and the Shift Project Data Portal website: http://www.tsp-data-portal.org/Breakdown-of-Electricity-Generation-by-Energy-Source#tspQvChart

The renewable energy emissions also vary for each country but less so than for grid electricity. This is primarily due to the location of the renewable sources as offshore renewables have a greater carbon footprint. The emissions data for renewables was taken from Ecoinvent 5, a life cycle inventory database (http://www.ecoinvent.org/). For Wind a technology mix of onshore and offshore at plant (1kv-60kv) and for solar a technology mix of CIS, CdTE, mono and multi crystalline at plant (1kv-60kv) were utilised.

Common target products for CO_2 utilisation include bulk chemicals, fuels and mineral carbonates. Here, hydrocarbon products are targeted due to the focus of the CyclicCO2R project and therefore mineral carbonates were not included. It is acknowledged that the publics are not particularly comfortable with discussing chemicals (TNS BMRB, 2015), therefore instead of using chemical names within the App, such as polyurethane or polyethylene terephthalate generic terms such as plastic bottle were used to enhance accessibility. Eight products were chosen to represent a range of hydrocarbon products that could be made from CO_2:

- Methane (CH_4)
- Diesel ($C_{12}H_{23}$)
- Aviation fuel ($C_{12}H_{26}$)
- Methanol (CH_3OH)
- Nappy Absorbent (C_3H_4O)
- Plastic bottle ($C_{10}H_8O_4$)
- Mattress ($C_4H_6O_3$)
- Fuel cell (CH_2O_2)

The products cover a range of technology readiness levels (TRLs), therefore enabling users to envisage how a CO_2 economy could develop over time and the types of products that could become available. Each product was described within the App to provide the user background information on the product, how it can be formed and its uses, Figure 10.4.

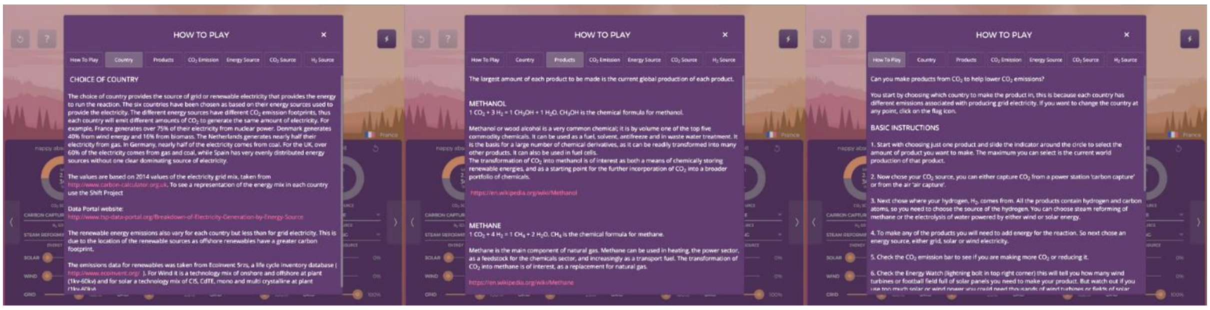

Figure 10.4 How to play CO2Go

For simplicity, a choice of two CO_2 sources was included; capturing the CO_2 from a power plant flue gas (point source emission) or capturing the CO_2 from the air (direct air capture). The CO_2 footprint of the capture method is included in the calculations. Carbon capture plants generally will give around a 75–84% reduction in greenhouse gas emissions but energy is required for the process (Leung *et al.*, 2014) Air capture technologies are at a low TRL, therefore the CO_2 emissions were calculated by taking an average of data from three processes (Zeman, 2007) . Two methods of hydrogen production are given steam reforming of methane (CH_4) or water electrolysis (H_2O) utilising data from Cetinkaya *et al.* (2012). To avoid extra emissions, wind or solar power is presumed to provide the electricity needed for the electrolysis.

Full process data was not available for all products due to the variation in TRL therefore, to allow comparability between products 100 % reactivity and selectivity for all products was assumed. The energy required for the reaction is assumed to come from electricity, either from the grid of the country chosen, wind energy, or solar energy. The Gibbs free energy (ΔG) for each of these reactions is negative, such that energy is produced during the reaction. However, for many of these products, the precise energy requirement for the reaction is not known. In order to place all products on a common scale, assumptions were made that the energy of reaction is the same as the combustion energy of the product, that is, the energy that is released when the product is burned in pure oxygen (O_2) to produce CO_2 and water (H_2O).

Game play involves users altering production volumes, location and changing electricity, hydrogen and CO_2 sources to observe the impact on CO_2 emissions. Game screens shown in Figure 10.5, depict the change in emissions based on the amount and method of production of the selected products.

The CO_2 emissions bar represents the total 1990 EU emissions for the processing industry, including the chemicals industry (EU-28, http://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer). The total 1990 CO_2 emissions for EU were 4470 million tonnes, and the emissions due to the processing industry were 7.2% or 322 million tonnes. The EU climate targets are based on the percentage of CO_2 reductions as compared to these 1990 emissions.

Targets within the App are set at 40 % reduction by 2030, 60 % reduction by 2040, and 80 % reduction by 2050. Background colours change through a progression of red, to orange to green to indicate the success of the user in meeting the targets.

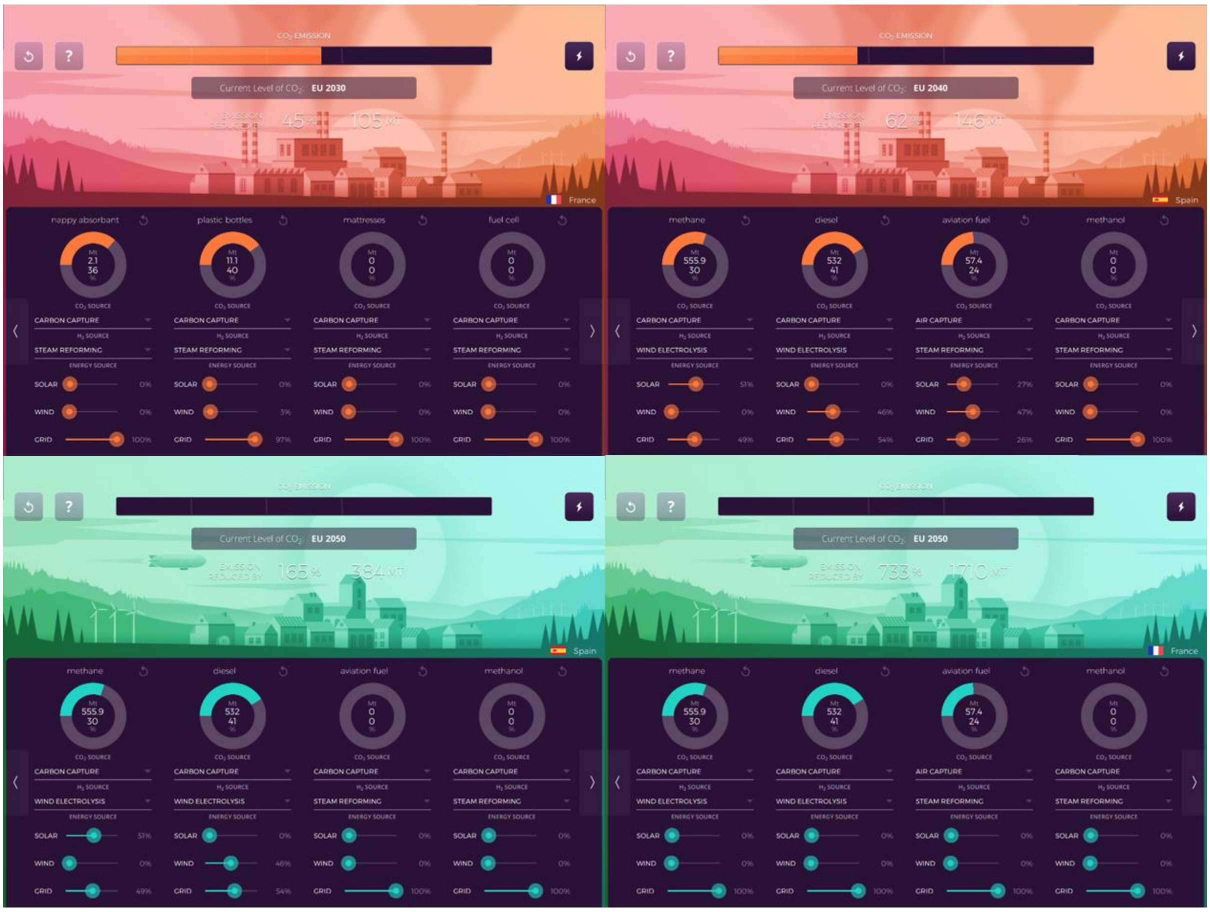

Figure 10.5 Gameplay screens

To enable CO_2 utilisation products to contribute to reduced greenhouse gas emissions, renewable energy must be used. The App explores this interlinkage by using an ‘Energy Watch’ function, Figure 10.6. It was known from prior research (C.R. Jones *et al.*, 2014) that stakeholders are concerned about the amounts renewable that are required for CO_2 utilisation and therefore a meaningful, tangible method of communicating quantities of energy needed was required. Metrics of number of wind turbines and football pitches of solar panels required were used to enable the users to visualise the required energy as it was felt kWh or MWh would have little meaning to users particularly to school children.

Figure 10.6 Energy Watch popup within the App

10.4 Focus Groups

To determine the effectiveness of the App in increasing knowledge and understanding of CO_2 utilisation within the target audience of young people, two focus groups were held within a local secondary school science club. Focus groups are a recognised methodology of gaining qualitative data from target audiences in an efficient manner though a discussion (Morgan, 1998; Wilkinson, 1998; Onwuegbuzie *et al.*, 2009). Focus groups are in essence small in size (<12 participants) and carried out over a short 1-2hr time period (Morgan, 1998) thus making them ideal for gathering information from young people. Participation in the focus groups was voluntary and conducted in accordance with the University of Sheffield Ethics Policy. A full approved ethics review and consent from the participants' parents were gained in advance of the session. The participants were able to withdraw from the focus group at any point.

Two focus groups were held one with Year 7 (11-12 year old pupils), *n*= 9, male = 1, female=8 and another with Year 8 and 9 (12-14 year old pupils) *n*=7, male = 6, female = 1. The focus groups took place during an afterschool Science Club Session. The students firstly answered a series of short questions to ascertain their knowledge levels about CO_2 utilisation and climate change. Questions were designed in an open-ended response format to ensure answers captured knowledge rather than best-guess from multiple choice options. Participants then used the App individually on computers, having a chance to play with it and learn how it works. They were then asked to fill in another short questionnaire repeating a number of the initial questions to gauge learning followed by participating in a group discussion.

Initially the students were asked ‘What do you know about CO_2?’ Responses were categorised by keywords and themes with six participants responding that CO_2 is carbon dioxide. Three participants recognised CO_2 was made of carbon and oxygen, four mentioned CO_2’s role in photosynthesis with a further four mentions of climate change or CO_2 as a greenhouse gas. Only two participants stated they didn’t know anything about CO_2. The same question was asked after playing on the App. After playing the App, no participants answered that they ‘didn’t know’. New themes subsequent to App use, included sources of CO_2 production (n=2), that CO_2 can be used (n=7) and that it is bad for the environment (n=2). Seven out of 16 respondents mentioned climate change, greenhouse gas or that CO_2 is bad for environment after utilising the App compared with 4 before use. A paired sample t-test was performed to assess whether the there is a true mean difference in this response. The test concluded that p (one-tail) = 0 .04 ($p<0.05$) confirming that a significant increase in responses mentioning the role of CO_2 in environment/climate change is observed after App usage. Thus indicating an increase in linking CO_2 to environment/climate change when asked generically about CO_2. Additionally, before App use students were asked a more specific question regarding the negative aspects of CO_2: ‘What is the problem with CO_2?’ One student answered ‘*Not sure*’ (Participant 12) with all other students giving responses which included terms such as global warming (n=9), too much (n=6), toxic/pollutant (n=3) climate change (n=2), greenhouse gas (n=3). This clearly demonstrates that all participants had a basic understanding of the negative effects of CO_2 in the atmosphere before App use, however; when contrasting responses to the first question about what do they know about $CO_{2,}$ these negative aspects appear to not be at the forefront of the students thoughts.

Students were asked ‘Where does CO_2 come from?’ Only one participant did not identify any sources of CO_2. Most students had some understanding of how CO_2 is produced, with only one incorrect theme of CO_2 coming from the sun emerging. Some responses were detailed showing considerable scientific knowledge, for example:

‘Carbon dioxide is released as a waste product in respiration. Carbon dioxide is released when organic matter is burnt. Carbon dioxide is released when other carbon fuels such as alchohol (sic) is burnt’ Participant 4 (male, Year 9)

Minor changes in response were observed before and after App usage. Figure 10.7 details new mentions of keywords when asked 'Where does CO_2 come from?' after App usage. Following App use new mentions of making energy and products were observed. Although combustion/burning were mentioned prior to App use, the specific link to energy production was only observed after use.

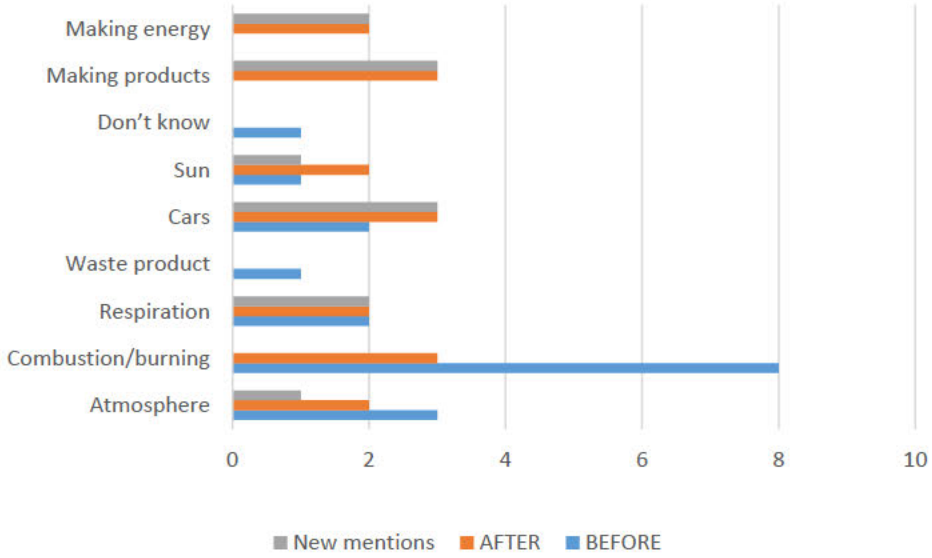

Figure 10.7 Where does CO_2 come from?

When asked 'could CO_2be used for anything', 14 out of 16 participants answered that it could be used before experiencing the App, however 6 of these did not know what CO_2 could be used for. One possible reason for the high positive response to CO_2 use was that all participants were given a pre-study information sheet explaining what the session was involving to gain parental consent. Therefore, all participants had some level of prior information that the session would be focused on CO_2 utilisation. Responses given to this question however, showed limited understanding of CO_2 utilisation, with some incorrect ideas for example:

"macking (sic) clothes powering mechanical devices" Participant 3 (female, Year 7)
"to be burned" Participant 15 (male, Year 7)

In general, older participants had a more comprehensive knowledge of uses of CO_2 as would be expected due to higher level of science education. Following App usage, responses were more detailed, for example Participant 4:

"Carbonation of drinks" Participant 4 response before App use (male, Year 9)
"Carbonation of fizzy drinks Creation of carbon fuels Creation of Plastics Creation of other chemicals eg. Methanol" Participant 4 after App use (male, Year 9)

After use, 11 of the 16 students specifically mentioned products discussed within the App with a further two stating it could be made to make products but not specifying the products. Only one student stated that they didn't know what CO_2 could be used for after using the App. However, this student regularly answered 'Don't know' throughout the questionnaire, but responded with the highest possible positive score for 'I learnt something from playing the App' (score 5/5), showing a discrepancy between answering patterns. One possible conclusion is that the student was concerned in giving the perceived wrong answer so defaulted to 'I don't know' responses in open response questions.

Participants were asked about their knowledge of different types of energy. For each term, participants were asked if they, 'Had heard of the term and could explain it', 'had heard of the term but didn't really know how it mean's or if they 'hadn't heard of the term'. Renewable energy was the most recognised term with all participants recognising the term and 13 of 16 participants being able to explain the term, Figure 10.8. After use of the App, increases in being able to explain grid electricity (increase of 6 participants) and carbon capture (increase of 5 participants) were observed, demonstrating that the App enabled participants to understand these terms. Paired t-Tests conducted on the before and after result giving a score of 2 for those who 'could explain the term', 1 for 'if heard of it' and 0 if 'not heard of it' to determine if there was a significant difference in the knowledge before and after App usage. Results gave p (one tail) = 0.0007 for grid electricity and p (one tail)= 0.072 for carbon capture ($p<0.05$). This confirms there was a significant difference (increase) in students knowledge of both terms.

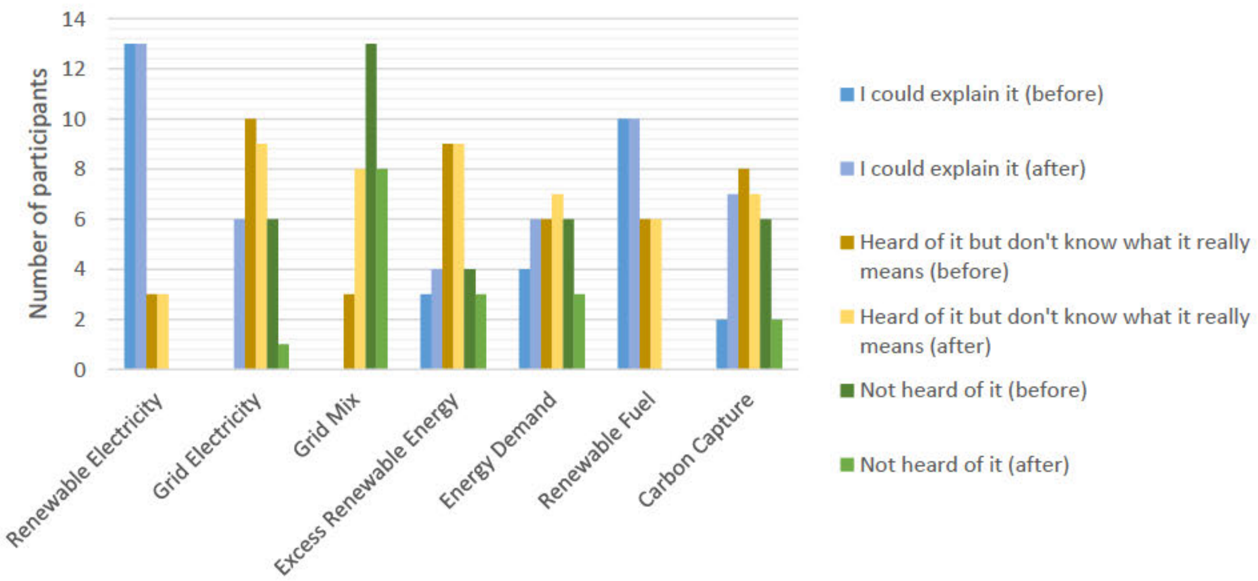

Figure 10.8 Knowledge of energy terminology before and after App use

Fifteen participants used the Energy Watch function whilst playing the game. They were then asked what the numbers in Energy Watch made them think. Statements included:

"that it will take up lots of land" Participant 1 (female, Year 7)
"That to have a good amount of solar energy you need to produce loads and loads of solar panels. Compared to wind power, you dont need as much wind turbines" Participant 6 (Male, Year 8)
"I felt quite surprised" Participant 9 (female, Year 7)
"i was shocked" Participant 10 (female, Year 7)

The general theme of all the comments on the energy requirement was that it was surprising and a large quantity. These highlight the necessity when communication CO_2 utilisation to discuss the whole process and interlinkages with the renewable energy sector.

After playing the App, students were asked to rate it using a 5-point scale (5 being very positive). The participants were positive about the App. Means (cross mark in Figure 10.9) for ease of use, enjoyment and that they had learnt something whilst using it were highly positive. The introduction was not rated as highly (3.4 mean) however it was not observed to be a negative, just more boring. One outlying less positive score was observed regarding learning within the App but this aspect had the smallest range of results and highest scoring quartile range indicating in general the participants highly rated the App for learning.

Subsequent to App use the participants took part in a guided discussion to comment on their experience with the App, their perceptions of CO_2 utilisation and thoughts on future App iterations. Participants commented the they liked changing the inputs (electricity, CO_2 and H_2 source) and they liked how the screen changed colour as emissions changed. The "Energy Watch" was also positively commented on, though suggestions were made to include a map to illustrate the amount of land needed in comparison to size of countries in addition numerical representation. The focus groups felt that further 'gamification' aspects would enhance playability of the App with a leader-board or ability to 'win' a popular request. These aspects were not included in the design of CO2Go as the focus was to create an educational and communication tool to allow users to explore CO_2 utilisation technologies, however it is recognised that these aspects could increase gameplay time and therefore increase understanding and knowledge. The inclusion of financial impacts and costs were also raised. Students felt the ability to understand the financial impact of the energy requirement would increase the understanding of the consequences of chosen actions within the App.

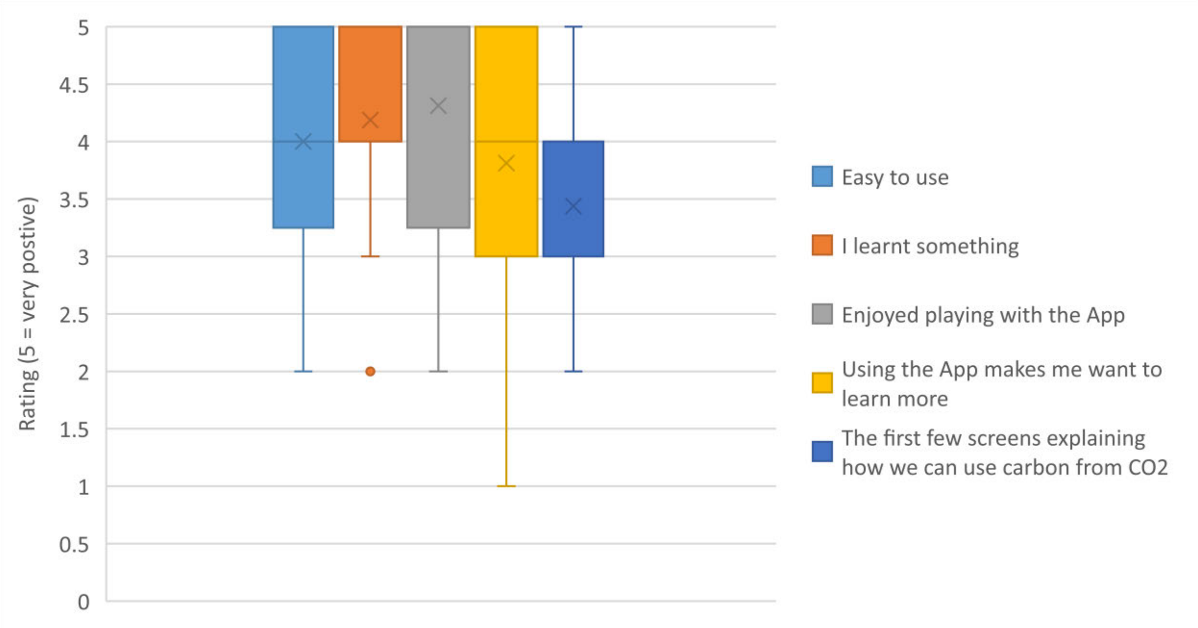

Figure 10.9 Rating for aspects of App

10.5 Conclusions

Public perception and acceptance of an emerging technology is known to be an essential component to viability. This especially is evident when the technology itself is complex combining many facets for successful deployment. Therefore, understanding the issues facing consumer and stakeholder acceptance or rejection of CO_2 utilisation is fundamental. The first public perception study in 2014 (Jones et al., 2014) confirmed general positive attitudes towards CO_2 utilisation but highlighted the complexities of communicating the subject and the lack of initial awareness. Participants in this study had very low initial awareness of CO_2 utilisation. However, after engaging with the focus group and guided discussion indicated preferences to CO_2 utilisation over CCS and could see the value in creating products from CO_2. Therefore, to enhance acceptance of CO_2 utilisation methods of increasing knowledge and understanding are required.

Initial communication methods such as the described 'Top Trumps' cards, increased awareness and knowledge of CO_2 utilisation within participant groups. The 'Top Trumps' approach allowed the complex aspects to be communicated visually but did not enable user interaction to enhance the learning experience and create further understanding thorough experience. Stakeholder engagement methods which explore both the positive benefits and potential hurdles to implementation are advantageous to enable stake holders to form educated rather than pseudo-opinions. By utilising techniques such as serious games or gamification it was anticipated that the many facets of CO_2

utilisation could be interactively explored, particularly the interactions between CO_2 utilisation, carbon capture, renewable energy and climate change through CO_2 emissions.

CO2Go applied a novel gamification approach for the first time in CO_2 utilisation allowing both positive and negative aspects of producing products from CO_2 to be interactively explored. Specific design elements of App enabled users to explore CO_2 utilisation concepts by producing a range of products in the choice of six locations with varying CO_2, electricity and hydrogen inputs. The use of the colour though the App clearly indicated success or failure in reducing CO_2 emissions allowing uses to alter their decision-making to affect the outcome.

It was found that the response to and engagement with the App was very positive within the focus groups. Similar to previous studies, prior knowledge of CO_2 utilisation was low. However, 14 out of 16 participants reported that they ranked their learning within the App as high or very high. Significant increases in being able to mention products that could be made from CO_2 and discuss the terms grid energy and carbon capture were observed. Overall, CO2Go was rated highly within the focus groups for ease of use, learning and enjoyment confirming it as fit for purpose as a tool to communicate CO_2 utilisation opportunities. CO2Go was found to enable users within the focus group to engage with the complexities of CO_2 utilisation in a fun and engaging manner. Therefore, it can be concluded that CO2Go was successful in communicating the complexity of the topic. This was particularly evident in regard to the amount of renewable energy needed with students reporting that they liked being able to change inputs (electricity, CO_2 and H_2 source) to see how it changed emissions.

The App was created as an educational and communication tool to allow users to explore CO_2 utilisation technologies using responsive visual changes to user inputs, a purpose that has successfully been demonstrated. However, this aim meant App was purposefully not designed to included gameplay concepts such leader-boards, feedback loops or level progression which increase playability and challenge. Students in the App focus group commented in discussions after using the app that these aspects would increase their enjoyment and encourage further participation. Students also commented that they would like to see financial aspects included to enable decision making based on economic as well as environment impacts. Therefore, if further iterations of the App or new CO_2 utilisation apps are designed it is suggested that such gameplay concepts are included to increase playability. However, care should be taken not to dilute the education purpose by over gamifying the product and reducing relevance to real situations.

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11 Conclusions

11.1 Reflections on growth

During the eight years of research that has formed this thesis the landscape of CO_2 utilisation has changed significantly. At the beginning of this research period in 2012, CDU was a low TRL, emerging technology though with a steady growth in research interest since the start of the 21st Century. Between 1970-2000 a SCOPUS search reveals an average of 11 publications per year mentioning CO_2 utilisation, CO_2 conversion or some derivative. Publication volumes grew in the early 2000's and Michele Aresta's seminal text, 'Carbon Dioxide as a Chemical Feedstock' was published in 2010 (Aresta, 2010). Our publication, Carbon Capture and Utilisation in the Green Economy (Styring *et al.*, 2011) further catalysed broad interest in this emerging field. Written as an accessible policy document, it highlighted CCU and discussed opportunities and challenges for the chemical conversion of CO_2, mineral carbonation and the production of biofuels from algae. The publication highlighted the potential benefits of CCU in the international context with its possible contribution to climate targets, energy security and sourcing renewable chemicals. Designed with accessibility in mind, the nature of the document enabled it to be used by many as an introduction to the subject, catalysing interest in CO_2 utilisation with new audiences. The publication concluded with some of the first recommendations to policy makers to enhance CCU deployment. The recommendations were wide ranging covering research, economics and technology assessment each proposed with the aim of accelerating research, development and deployment. Reflecting upon these recommendations 10 years later, Table 11-1 details how the recommendations can be correlated with examples in which they have since been realised. These examples demonstrate growth in awareness and interest in the potential of CO_2 utilisation technologies, not just in the context of emission mitigation but as a sustainable source of chemicals from funding bodies, governments, NGOs and industry.

Table 11-1 Policy Recommendations from Carbon Capture and Utilisation in the Green Economy (Styring *et al.*, 2011)

Policy recommendation (Styring *et al.*, 2011)	Examples of realisation
Developing technology roadmap	○ IEA reports (IEA (International Energy Agency), 2019b, 2019a), ○ SCOT project (Armstrong *et al.*, 2016), ○ The UK CCUS deployment pathway (BEIS, 2018) and numerous others
Creating best practices for GHG accounting	○ Guidelines for LCA and TEA assessment (Zimmermann *et al.*, 2018, 2020) and the ongoing work of the Global CO2 Initiative to harmonize assessment methodologies
More financial support for CCU	○ Increase in funding for CCU through programmes such as H2020 ○ New ALIGN-CCUS ERA-Net ○ German CO2-WIN programme ○ Cosia Carbon X-Prize
Economic incentives	○ Cosia Carbon X-Prize ○ REDII in EU

	o 45Q in USA o Canadian Carbon taxes
Review of technologies close to commercialisation	o Circular Carbon Network o Dechema's Low Carbon energy and feedstock for the European chemical industry report (Bazzanella *et al.*, 2017) o Decarbonisation of Industrial Sectors(McKinsey, 2018)

The 2017 Mission Innovation Expert Workshop on Carbon Capture Utilization and Storage, further identifying global research priorities for CCUS (Mission Innovation, 2017). The inclusion of CCUS in Mission Innovation cemented the role CCUS can play in clean energy innovation. The aim of the workshop was to stimulate global research collaborations by bringing together over 250 invited global experts (including the author) to ascertain priorities for targeted future funding. Thus leading to revolutionary advances in research, accelerating the speed of innovation and enabling CCUS to contribute to CO_2 mitigation targets. Keeping these aims in mind, panels of experts were asked to identify priority research directions for their relevant research community; carbon capture, storage, utilisation or cross-cutting themes. For CO_2 utilisation the following were identified:

- PRD U-1: Valorizing CO_2 by Breakthrough Catalytic Transformations into Fuels and Chemicals
- PRD U-2: Creating New Routes to Carbon-based Functional Materials from CO_2
- PRD U-3: Designing and Controlling Molecular-Scale Interactions for Electrochemical and Photochemical Conversion of CO_2.
- PRD U-4: Harnessing Multiscale Phenomena for High-Performance Electrochemical and Photochemical Transformation of CO_2
- PRD U-5: Accelerating Carbon Mineralization by Harnessing the Complexity of Solid–Liquid Interfaces
- PRD U-6: Tailoring Material Properties to Enable Carbon Storage in Products
- PRD U-7: Tailoring Microbial and Bioinspired Approaches to CO_2 Conversion
- PRD U-8: Hybridizing Electrochemical and Biological Processes for CO_2 Conversion to Fuels, Chemicals, and Nutrients
- PRD U-9: Engineering Complex Interfaces for Enhancing Hydrocarbon Recovery with Potential Carbon Storage

The mood of the workshop was cautiously optimistic that the detailed report generated would indeed catalyse growth. However, upon reflection, few new publically funded schemes have materialised. One notable outcome was the extension of the UK spearheaded existing publically-funded ACT (Accelerating CCS Technologies) initiative to encompass utilisation in further funding calls and its expansion to more countries. In the second and third calls, which have included utilisation, €58 million has been awarded however, these have predominately focused on CCS projects rather than utilisation due to the terms of the call. This calls into question whether the incorporation of utilisation and CCS into CCUS, is a help or hindrance to funding for utilisation.

In the cross-cutting theme at Mission Innovation, all aspects of CCUS enabling research were considered, predominantly focusing on the assessment of technologies and modelling. Here, the need to incorporate social aspects into decision making and developing tools to integrate LCA, TEA and SIA were highlighted as priorities. The theme of calls for specific guidelines for assessment of CCU technologies continued with the European Commission Scientific Advice Mechanism (Scientific Advice Mechanism, 2018). The CCU community across academia, industry and policy had been requesting guidelines for many years to enable transparent and comparative reporting across the CCU value chain, however funding and organisational direction was lacking. A project funded by the Global CO_2 Initiative and EIT Climate KIC took up the challenge and in 2018 published guidelines for specifically assessing environmental and economic impacts of CCU with further updates in 2020 (Zimmermann *et al.*, 2018, 2020). The guidelines serve to guide both practitioners in methodological choices and commissioners of studies within recognised frameworks and conventions such as ISO 14044. However, as highlighted in the Mission Innovation report it is insufficient to assess environmental, economic and social aspects in isolation. Interdependence between theses aspects necessitates integrated assessment approaches, hence further exposition on CDU assessment is presented here in Chapter 6 and Chapter 7. These papers elucidate how assessments can be integrated and expanded to cover the triple helix of environmental, economic and social impacts.

Of the technologies emerging on to the market explored in chapter 4, some have fallen at the final hurdles to commercialisation whilst others now have products available within the consumer market (Carbon Recycling International, Carbon8 and Covestro – formally Bayer Material Science). New organisations have burst onto the scene such as Lanzatech, Mineral Carbonation International, AirCo and Carbon Upcycling Technologies. It is observed that the market pull for new sustainable technologies is growing. Demands for companies to publish net zero targets are accelerating particularly in the run up to COP 26[1] and in line with programmes such as the Science Based Targets Initiative (SBTi)[2] and the Global Reporting Initiative (GRI)[3]. Public awareness of sustainability issues has increase with the prominence of the Climate Strike action by Greta Thunberg (Sabherwal *et al.*, 2021) and TV series such as David Attenborough's Blue Planet II (Dunn *et al.*, 2020; Males *et al.*, 2021). High profile, brand-leading organisations such as Unilever, Microsoft, BT, British Airways, IKEA, Facebook, and Total have all made pledges to become net zero, necessitating investment in low carbon technologies as well as potential to offset emissions. This market pull has led to major corporations partnering with CO_2 utilisation SME's such as PepsiCo UK with CCM Technologies (PepsiCo, 2020) and Unilever with Lanzatech (Unilever, 2021). These partnerships have launched CO_2 utilisation into the public domain with coverage in major news outlets such as the BBC and daily UK

[1] https://unfccc.int/process/bodies/supreme-bodies/conference-of-the-parties-cop
[2] https://sciencebasedtargets.org/
[3] https://www.globalreporting.org/

newspapers. The opportunities for CO_2 utilisation technologies to play a role in fulfilling the sustainability demands of these major brand-leaders has strengthened potential prospects for CO_2 utilisation uptake. Of these of specific interest is Unilever's announcement that it is removing fossil carbon from its home care value chain (Unilever, 2020). Trademarked as the 'Carbon Rainbow' the move to sustainable cleaning and laundry brands has CO_2 playing a key role as a carbon source. The 'Carbon Rainbow' also demonstrates many of the communication principles described in Chapter 9. However, it is recognised that communication and public perception activities around CO_2 utilisation technologies are still evolving. Limited products on the market that the consumer engage with result in most communication regarding CO_2 being single media articles. Hence, public awareness of the potential of CO_2 utilisation is low.

11.2 Final Conclusions

This work set out to explore the potential of CO_2 utilisation. In the first chapter motivation for utilising carbon dioxide and the range of potential products was explored, concluding the chemistry is only part of the story. The rational for deployment of CO_2 utilisation is complex, combining climate mitigation and the need for a circular sustainable chemicals industry with economics and social impacts. Challenges in capturing CO_2, fostering symbiotic relationships between industries, developing new chemistries, assessing environmental impacts and ultimately creating a market for the products also play a role. Today, with focus ever sharpening on our impending climate crisis, the potential advantages of using CO_2 as a circular carbon source have led to an emergence of products on the market that are accessible as industrial feedstocks and consumer products.

Considering all the facets determining the potential of CDU technologies, economics is identified as one of the biggest challenges. Technological issues and scientific advancements are also key but in many cases, it is economics that are a crucial huddle to deployment. Economic challenges exist in several spheres for CDU: investment in scale up, carbon capture costs, large energy requirements, taxes/regulations and consumer price points. The 'Valley of Death' is a term frequently used to describe the translation of academic research to industrial deployment (Butler, 2008). The 'valley of death' sits between TRL4-6, the stages where research emerges from the lab and begins testing in real scenarios whilst scaling up in size. Here costs can be prohibitive, as investment is needed on an increasing scale. Many CDU technologies fail here or take considerable time periods to raise the capital needed. Translational funding approaches such as the Accelerating CCS Technologies scheme in Europe and prizes such as the Cosia Carbon X Prize look to address this, but more is needed. The 'race to net zero' in response to the climate emergence has increased opportunities for CDU with demand for low carbon footprint products to meet organisations corporate pledges, however economics still need to be favourable. The desire for financial incentives was highlighted in Chapter 8 during the survey of SMEs. Many SME's struggle with overcoming the Valley of Death or take considerable time to raise the investment to overcome it. Carbon taxes and government funding schemes have been identified as desired routes to tackle these issues. During the last eight years CDU has been incorporated into schemes like REDII (EU) and the 45Q (USA) whilst Canada has implemented carbon taxes which have been perceived to increase investment and deployment opportunities in the country. Economics are not a hurdle which can easily be overcome. Tough choices will need to be made to reach climate targets and remove human reliance on cheap fossil carbon. For CDU and other green technologies to thrive, huge investment is needed. Prices will decrease with innovation and mass deployment, as has been observed in the renewable energy sector. However, this is some way off and until this point incentives and/or emission taxes will be needed.

The subject of economics also raises social impact issues which are currently under evaluated in CDU. Sustainable products should be available for all, not just the wealthy and the development of sustainable products should not result is increases in negative human impacts. Incorporating holistic social impact assessment and public acceptance studies into CDU development should be a key next step after economic and environmental assessment. Social impacts need to be considered in a broad context, exploring how CDU technologies can impact humans across the whole supply chain and life cycle of the product. It is too easy to assume that just because CO_2 is being used to create a product it is automatically sustainable and good for both the planet and humans.

Research gaps especially lie in the social impacts and social awareness of CO_2 utilisation with first steps into these areas presented in chapters 7-10. Currently, there is limited research into these areas with only a handful of active research into social aspects of CDU. But, with products made from CO_2 emerging onto the market, we will see corporates investing heavily in this area to determine how to communicate the sustainability of their new products to customers. Media, marketing and increasing public understanding through education regarding sustainability issues is key and innovative engaging communication methods are required.

Ultimately, the potential for the deployment of CO_2 utilisation is vast. CO_2 utilisation will contribute to a circular, sustainable economy and can have an impact on CO_2 emission reduction. Nevertheless, what potential is realised is dependent on many technological, economic, environmental and societal aspects. This work has demonstrated interlinkages between different aspects of CO_2 utilisation. It can be concluded that a thorough appreciation of the interactions between these aspects is necessary to appreciate the potential of CO_2 utilisation deployment. Without such appreciation and methodologies to assess them, unlocking complexities such as holistic sustainability assessment, economic and legal barriers to SME's, consumer/social acceptance and industrial symbiosis and the interplay between them will ultimately hinder CO_2 utilisation reaching its potential.

11.3 Ongoing and Future Challenges for CO_2 Utilisation

Practicalities of deployment in industrial symbiotic, circular economy situations will be one of the next major challenges of CDU. Industrial clusters such as the Port of Rotterdam, Port of Antwerp and Tees Valley have all investigated how CDU could be deployed but the complexities of linking multiple companies such as the CO_2 emitter, waste feedstock producer and the CDU technology with a further processing technology and then accounting for emissions have yet to be fully explored. In many CDU LCA models, a whole systems approach is taken, combining the point source CO_2 emitter, the capture technology and the CDU technology into one system boundary. This valid approach gives a clear indication on the potential of the whole system to reduce CO_2 emissions and hence avoid emissions to the biosphere by deploying the new CDU technology. However, in practical corporate accounting mechanisms such as the SBTi's and GRI, whole systems approaches do not exist. Individual companies are required to report their emissions; therefore, the CO_2 emitter will report separately from the CDU technology. Therefore, in this scenario, the CO_2 emitter will reduce their emissions as they are captured and passed to the CDU technology to transform into a product. The CDU technology would count the CO_2 as entering the system with a zero burden, not as a negative reduction in emissions to the atmosphere. Using this methodology, the best the CDU technology could achieve would be a net zero/extremely low GHG impact product if the CO_2 emissions were sequestered in the product (for example a cement or other mineralised product) or if the CO_2 was originally from a biogenic source. However, many CDU companies currently market themselves as carbon negative, as they count the CO_2 entering the system as a negative input using the principal of CO_2 emission avoidance. Widely accepted methodologies for accounting across the value chain will be required which take into account the complexities of CDU systems whilst sharing potential environmental impact advantages of utilising CO_2 between actors. Ideally, these will be globalised or at least regionalised to avoid confusion and aid global organisations.

CO_2 utilisation is also not a standalone technology and is dependent on the development of other sectors. In chapter 3, sources of CO_2 and carbon capture were considered. For CDU technologies to be deployed a source of CO_2 is needed whether from a 3^{rd} party point source, internally generated in the process, or captured from the air. The capture and purification of CO_2 adds costs, hence new technologies which can directly utilise flue gas are advantageous. In order to produce truly carbon negative materials (not just those that avoid carbon emissions), CO_2 will need to come from biogenic or atmospheric sources. Therefore, it is expected that the prominence of DAC technologies will increase in future scenarios. Currently cost is an inhibiting factor for DAC with costs estimated at between US$100/t and US$1000/t with Climeworks stating current costs are between US$500-600 but hoping to reach US$100 in less than 10 years (Tollefson, 2018). Access to vast quantities of renewable energy and clean, low carbon hydrogen are interlinked challenges for creating a sustainable chemical industries utilising renewable carbon sources. Kätelhön *et al.*, (2019) have recently calculated more than 18.1 PWh of low carbon energy are required to exploit the potential of CDU, much of this needed for water electrolysis to produce H_2 for the formation of hydrocarbons. Increasing efficiency of processes to reduce energy demand will need to be a key focus of future research to reduce this demand.

In conclusion, CO_2 utilisation faces many and varied challenges to reach its full potential however, much progress has been made in laying foundations for growth. As with many emerging technologies, slow initial growth from pioneers in both research and industry leads to a critical mass and sharp growth increases. CO_2 utilisation has become more prominent in the public, private and governmental spheres in the last eight years. The future will tell how this leads to the potential for CO_2 utilisation to be realised.

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Supplementary Material

1. Supplementary Material for Chapter 6: Integration of techno-economic and life cycle assessment: Defining and applying integration types for chemical technology development

2. Supplementary Material for Chapter 7: Developing a Triple Helix Approach for CO_2 Utilisation Assessment

3. Supplementary Material for Chapter 10: Jones, C. R., Olfe-Kräutlein, B., Naims, H. and **Armstrong, K**. (2017) 'The Social Acceptance of Carbon Dioxide Utilisation: A Review and Research Agenda', *Frontiers in Energy Research*, 5. doi: 10.3389/fenrg.2017.00011.

4. Supplementary Material for Chapter 10: Jones, C.R., Radford, R. L., **Armstrong, K.** and Styring, P. (2014) 'What a waste! Assessing public perceptions of Carbon Dioxide Utilisation technology', Journal of CO2 Utilization, 7. doi: 10.1016/j.jcou.2014.05.001.

- Electronic Supporting Information (ESI) -

Integration of techno-economic and life cycle assessment: defining and applying integration types for chemical technology development

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1 A conceptual comparison of techno-economic assessment (TEA) and life-cycle costing (LCC)

A popular tool used to analyze the economic dimension of sustainability across many technology fields is life cycle costing (LCC) (Hunkeler et al., 2008; Swarr et al., 2011). Often cited is the purpose to analyze monetary flows for all the actors along the different life cycle stages of a product (Miah et al., 2017). These life cycle stages cover raw material acquisition, manufacturing, transportation, usage and end-of-life. In the broader sense, this would also include external costs that could be derived from monetizing impacts on the environment or the society caused by the product during its lifetime. However, literature provides many examples of LCC being limited to an investor-perspective only, especially studies of early technology developments (Jeswani et al., 2010). In these cases, the analysis is focused on data from cost and market analysis within gate-to-gate boundaries, assuming cost data for upstream raw material to be aggregated in the purchase price. This type is sometimes referred to as financial LCC, as it mirrors the inherent perspective underlying most TEAs which is that of a profit-oriented stakeholder (Swarr et al., 2011). At the same time, there is no methodological constraint preventing the application of TEA to cover lifecycle stages beyond the factory gate, for example, to assess the effect of customer costs or benefits accruing in the consumption phase or external costs to society indirectly caused by the product. The different inherent and optional perspectives of TEA and LCC are shown in Figure 1.

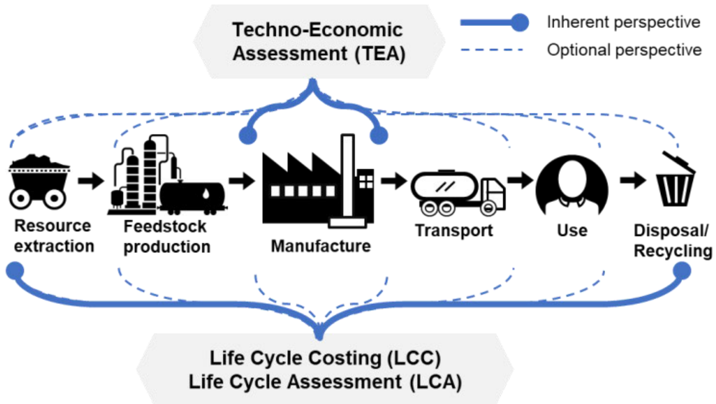

Figure 1: Product life cycle depicting inherent perspectives of TEA (investor-perspective within manufacturing gates) and LCC and LCA (full-life cycle perspective for all actors); both TEA and LCC can equally cover any combination of stages

The technological dimension appears to be of relevance mainly in TEA and much less in LCC. Some TEA studies report separate technical indicators to compare alternative process options based on their technical performance. However, the leading TEA criterion for decision-makers in the chemical industry remains economic in nature as is also the case with LCC. TEA can be thought of as an iterative process along the RD&D stages, meaning that technical parameters are translated into an economic impact which can then be interpreted to guide process design. Although a discussion of technical feasibility and a separate reporting of technical indicators does not appear to be relevant in LCC, no evidence can be found that applied economic methods are different for LCC and TEA. This is also true for the basic four-phase approach which is similar for both. General methodological aspects of TEA and LCC are compared in Table 1.

When looking at the overall use of terminology in the literature, a web-of-science search reveals that the term “life-cycle cost*” is mentioned 7736 times, with a focus on the categories civil engineering (1820), energy fuels (1361) and construction building technology (992). The increasingly used term “techno-economic a*” is only mentioned 3450 times, with a focus on the categories energy fuels (1,894), chemical engineering (767) and green sustainable science technology (618). This indicates that terminology selection for economic assessments tends to depend on the scientific fields, with LCC being dominant in civil engineering and TEA in process industries, such as chemical engineering. Besides the scientific context, only the typically opposite perspectives – investor perspective for TEA or full life cycle perspective for LCC– influence the name choice. A strict differentiation between TEA and LCC methodology does not exist. Each tool could be applied in a way that covers typical aspects of the other. In consequence, both terminologies could be used interchangeably, and it is therefore crucial to describe the intent and methodological context of the study.

Table 1: Comparison of general and methodological aspects of TEA and LCC

	TEA	LCC
General purpose	To assess economic viability	To assess economic viability
Main focus	Analyzing profitability	Uncovering all economic impacts along the product life cycle
Typical perspective	Investor-perspective	Full life cycle perspective (monetary flows of all stakeholders)
Typical system boundaries	Gate-to-gate	Cradle-to-grave
Adaptability of system boundaries	TEA could be extended to cover economic impacts across all life cycle stages	LCC could be limited to gate-to-gate studies
Assessment approach	Four phase approach (goal & scope, inventory, impact assessment, inventory)	Four phase approach (goal & scope, inventory, impact assessment, inventory)
Literature mentions (web-of-science count)	7336	3450
Associated categories (mainly)	civil engineering (1820), energy fuels (1361) and construction building technology (992)	energy fuels (1,894), chemical engineering (767) and green sustainable science technology (618)

2 Summary of the literature analysis and assigned reporting and integration types

Lists of the randomly selected academic studies used for the literature analysis conducted in chapter 2.1 of the main document as well as the results of the analysis are presented in Table 2 and Table 3. The aim of the literature analysis was to determine characteristics of integration methodologies used in studies combining TEA and LCA. As such, although the search was carried out in the sphere of chemical technologies, we were purely interested in the methodology used and not in the sector or technology assessed.

To determine key characteristics the methodological approach of saturation was applied. This is a recognized methodological approach in qualitative research for identifying themes and characteristics. In this method, studies are analyzed until no new characteristics can be found.

The papers were selected in the following way. An initial Web of Science search was conducted within the selectable Web of Science categories of ‘green sustainable science technology’, ‘energy fuels’ and ‘engineering chemical’ and the search queries within the title, abstract or keywords of (“LCA” or "life cycle assessment" or "life cycle analysis") and (“TEA” or “LCC” or "life cycle cost*" or “economic”). The results were manually screened to remove papers not within the scope of chemical process technologies, producing a set of 711 papers. Due to the search criteria it was recognized that many of these papers would not contain assessments but just mentioned the terms of the search, therefore further screening was required.

From this set, papers were randomly ordered using computer generated random selection. Random selection was used to eliminate bias. It was recognized that selection via citation would be more reflective of the technology assessed rather than the methodology. Also, selection via date may exclude some characteristics if certain methodologies came in and out of fashion. Therefore, it was concluded that completely random selection offered a non-biased approach.

Firstly, each paper underwent further screening to ensure that it contained both economic and environmental assessments and was not of review character, otherwise, they were discarded (>50% of papers were discarded in this manner). Subsequently, the paper was analyzed in detail to ascertain the goals, methodologies used, indicators calculated and style of interpretation. Theoretical saturation of methodologies and characteristics was reached at a sample size of 50 papers. To confirm saturation a set of further 20 papers was analyzed.

Table 2: Summary of the literature analysis of the random sample of papers meeting the search criteria. Table resorted into alphabetical by author.

Authors	Methods used: LCA/LCC/TEA	Mention of technology maturity (TRL)	Goals: Individual, Combined, Both	Combined indicators calculated	MCDA or MOO
Acar et al., (2014)	LCA and costing	Mentions developing systems	Both	No	Yes
Ahmad et al. (2018)	LCA and TEA	Mentions new technology	Combined	No	No
Akgul et al. (2012)	LCA and TEA	No	Both	No	Yes

Arora et al., (2018a)	LCA and TEA	Mentions developmental stage	Both	Yes	Yes
Azapagic et al. (2006)	LCA and TEA	No	Combined	Yes	No
Bernier et al. (2010)	LCA and economics	No	Combined	Yes	Yes
Burchart-Korol et al. (2016)	LCC and LCA, calculation of eco-efficiency	No	Combined	Yes	No
Cai et al. (2018)	LCA and TEA	No	Combined	No	No
Carapellucci et al. (2019)	TEA and cost CO_2 avoided	No	Combined	Yes	No
Chao et al. (2019)	LCA and TEA	No	Combined	Yes	Yes
Chen et al. (2019)	LCA & TEA	No	Both	No	No
Daylan and Ciliz (2016)	LCA and ELCC	No	Combined	No	No
Di Maria et al. (2018)	LCC and LCA	No	Both	No	No
Dias et al., (2013)	LCA and TEA	Mentions scale	Individual	No	No
Elms and El-Halwagi (2010)	TEA, LCA	No	Combined	No	No
García et al. (2014)	LCA, Eco-indicator 99	No	Combined	No	Yes
García-Velásquez and Cardona (2019)	LCA and TEA	No	Both	No	No
Gargalo et al. (2017)	TEA and LCA	No	Combined	Yes	Yes
Gerber et al. (2011)	LCA and TEA	Mentions emerging technology	Both	No	Yes
Ghanta et al., (2013)	LCA and TEA	Mentions scale	Individual	No	No
Guillen-Gosalbez et al. (2007)	LCA, Cost modelling, Eco-indicator 99	No	Combined	No	Yes
Halog and Manik (2011)	LCC, LCA, SLCA	Mentions emerging technology	Combined	Yes	Yes
Hise et al. (2016)	LCA and TEA	Yes	Both	No	No
Kim et al., (2013)	LCA and social costs	Mentions maturity	Both	Yes	No
Kong et al. (2017)	LCA and economic assessment	No	Combined	No	No
Lee et al., (2019)	LCA and TEA	No	Both	No	Yes
Li et al. (2017)	TEA and LCA	No	Combined	No	No
Li et al. (2018)	LCA and cost analysis	No	Both	No	No
Liu et al., (2014)	LCA and TEA	No	Combined	No	Yes
Liu et al., (2017)	LCA and TEA	Mentions scaling	Individual	No	No
Lu and El Hanandeh (2019)	LCA and LCC	No	Combined	No	Yes
Luo et al. (2009)	LCC and LCA	No	Combined	No	No
Malik et al., (2015)	LCA and TEA	No	Individual	No	No
Martinez-Hernandez et al., (2019)	LCA and TEA	Yes	Combined	No	No
Masri et al., (2019)	LCA and TEA	No	Individual	No	No
Mata et al. (2015)	LCA, economics and social	No	Combined	Yes	No

Mata et al.,(2011)	GHG and TEA	No	Both	Yes	No
Md Yunos et al. (2017)	LCA and TEA	No	Combined	No	No
Michailos (2018)	LCA (GWP only) and TEA	No	Both	No	No
Moncada et al. (2015)	Economic and environmental indicators	No	Combined	Yes	Yes
Mondal and Ramesh Chandran (2014)	TEA & carbon emission	No	Combined	No	No
Nieder-Heitmann et al., (2019)	LCA, LCCA and SLCA	Yes	Both	Yes	Yes
Oh et al. (2018)	LCA and TEA	No	Combined	No	No
Panu et al. (2019)	Economic costing and carbon emissions	No	Combined	No	Yes
Pastore et al. (2016)	LCA and LCC	No	Combined	No	No
Patel et al. 2016)	TEA and LCA	No	Combined	No	No
Petrillo et al. (2016)	LCA, SLCA, LCC	No	Combined	Yes	Yes
Po-Han et al., (2017)	LCA and TEA	Mentions scales	Combined	No	Yes
Rehl and Müller (2013)	LCC and LCA	No	Both	Yes	No
Reich (2005)	LCA and fLCC	No	Combined	Yes	Yes
Reinhardt et al. (2008)	LCA and Cost factors	No	Combined	No	Yes
Ren et al. (2015)	LCA, LCC, SLCA	No	Combined	No	Yes
Reyes Valle et al., (2015)	LCA and TEA	No	Both	No	No
Ristimäki et al. (2013)	LCC and LCA	No	Both	No	No
Ruiz-Femenia et al., (2013)	LCA and TEA	No	Combined	No	Yes
Sacramento-Rivero et al., (2016)	LCA and TEA	Mentions conceptual design	Combined	No	No
Safarian and Unnthorsson (2018)	TEA and LCA	No	Combined	No	Yes
Santibañez-Aguilar et al., (2011)	LCA and TEA	No	Combined	No	Yes
Shemfe et al. (2018)	LCA and TEA	Mentions scale up	Both	No	No
Tang and You (2018a)	LCA and TEA	No	Both	Yes	Yes
Tang and You (2018b)	LCA and TEA	No	Both	Yes	Yes
Telsnig et al. (2013)	LCA and TEA	No	Both	Yes	No
Thomassen et al. (2018)	LCA and TEA *via* ETEA	Yes	Combined	No	No
Tock and Maréchal (2015)	LCA and TEA	No	Combined	Yes	Yes
Tomaschek et al. (2012)	GHG emissions and TEA	No	Combined	Yes	No
Torres et al., (2013)	LCA and TEA	No	Combined	No	Yes
Verma et al. (2015)	LCA and TEA	No	Combined	Yes	No
Wang and Demirel (2018)	TEA and LCA	No	Combined	No	Yes
Yang et al. (2019)	TEA and LCA	No	Combined	No	No
Zhang et al. (2016)	LCA and costs	No	Combined	No	Yes

Table 3: Summary of reporting and integration types found in analyzed CO_2 utilization literature

Authors	**Reporting or integration type assigned to paper**
Arora et al. (2018)	MCDA (**Type C** integration)
Chauvy et al. (2019)	MCDA (**Type C** integration)
Chen et al. (2017)	Combined indicator (**Type B** integration)
Cuéllar-Franca et al. (2019)	Co-reporting
Fernández-Dacosta et al. (2019)	Qualitative discussion (**Type A** integration)
Fernández-Dacosta et al. (2018)	Qualitative discussion (**Type A** integration)
Gebreslassie et al. (2015)	MCDA (Type C integration)
Giannoulakis et al. (2014)	Combined indicator (**Type B** integration)
Haro et al. (2015a)	Co-reporting
Haro et al. (2015b)	Qualitative discussion (**Type A** integration)
Jens et al. (2019)	Co-reporting
Jiang et al. (2019)	Co-reporting
Khoo et al. (2011)	Combined indicator (**Type B** integration)
Leie et al. (2018)	Qualitative discussion (**Type A** integration)
Liu et al. (2017)	Co-reporting
Pan et al. (2016)	MCDA (**Type C** integration)
Panu et al. (2019)	MCDA (**Type C** integration)
Sharifzadeh et al. (2015)	Co-reporting
Telsnig et al. (2013)	Combined indicator (**Type B** integration)
Tock et al. (2015)	MCDA (**Type C** integration)
Tripodi et al. (2018)	Co-reporting
Wang and Demirel (2018)	MCDA (**Type C** integration)
Xiang et al. (2015)	Co-reporting
Yi et al. (2014)	Combined indicator (**Type B** integration)
Yusuf et al. (2019)	Combined indicator (**Type B** integration)

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Supplementary information to "Developing a Triple Helix Approach for CO_2 Utilisation Assessment"

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Table 1 ESI Selected subcategories and their application to CDU social impact assessment (full framework)

Stakeholder	UNEP subcategory	Aims of UNEP subcategory assessment	Relevance to identified CDU assessment scope	Suggested indicator(s)	Typical data inputs used for assessing indicator	Suggested external data sources
Local Community	Delocalisation & migration	Assess the contribution to delocalization, migration or 'involuntary resettlement' within communities	Changes in land use at scale for economic development can be a driving factor in the creation of displaced persons	Likelihood of forced evictions for technology implementation	Process design calculations, LCI data, geographical data (land use), regional/national data on forced resettlement/compulsory purchase orders etc.	OECD land resources statistics
	Local employment	Assesses how an organization directly or indirectly affects local employment.	CDU technologies could bring changes to employment opportunities both directly & indirectly, more so if the supply chain is localised	Operational impact on local employment - direct	Process design calculations, labour estimation calculations, employment & labour statistics	World Bank development indicators (employment), national employment & labour statistics
				Operational impact on local employment - indirect	Employment & labour statistics, IRENA employment statistics, COMTRADE-type data	World Bank development indicators (employment), national employment & labour statistics
	Access to material resources	Assess the extent to which organizations respect/protect/ improve community access to material resources & infrastructure.	CDU technologies can impact positively & negatively access to resources such as (renewable) electricity, water, land & other products. Additional strains on areas known to be water/land/energy (renewable & not) constrained may cause problems for communities. Operations may also impact access to material produce negatively (consuming limited resources) or positively (increasing domestic security of supply)	Operational impact on local land-use & zoning	Process design calculations, LCI data, geographical data (land use)	OECD land resources statistics
				Changes to local water supply & security	Process design calculations, LCI data, water scarcity data for country/region	UN AQUASTAT database, national reports/statistics (regional perspective)
				Changes to local electricity & energy supply	Process design calculations, LCI data, national electricity/energy statistics (e,g, DUKES)	World bank WDI & SE4ALL databases, national reports/statistics on electricity & energy consumption/provision
				Changes to local access to material produce	COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases,

						Observatory of economic complexity data
	Safe & healthy living conditions	Assess how organizations impact community safety & health	Potential risks and benefits of CDU plant operation on the communities safety & health should be assessed to determine potential impacts on the local community (considering both regular operation & accident potential)	Impact on air quality & pollution levels	Process design calculations, LCI data	World Bank WDI database
				Utilisation & risks associated with the use of hazardous substances in the operation	Chemical safety data, LCI data, HAZOP studies	COSHH database, ILO International Chemicals Safety Cards database
Value Chain Actors	Promoting social responsibility	Assess whether the organisation promotes social responsibility through its actions & among its suppliers	Choices made in technology development/deployment may have unintended impacts on value chains and communities involved in these chains. CDU processes offer the potential to utilise 'waste' streams	Potential for and impact of integration of waste materials into the supply chain	LCI data	LCI databases
				Risk of utilisation of illicit or conflict materials within supply chain	LCI data, COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases, Observatory of economic complexity data
Consumers	Consumer health & safety	Assess the existence & scope of systematic efforts to address consumer health & safety across the life cycle	Whilst always beneficial, assessing risks to the H&S of consumers is of particular importance if a new CDU product fulfils the same function of an existing product whilst being chemically non identical – e.g. DME as a fuel	Consumer health & safety risk	Process design calculations, LCI data, Chemical safety data	COSHH database, ILO International Chemicals Safety Cards database
	End of life (EoL) responsibility	Assess management efforts to address the social impacts of product or service end-of-life	Understanding EoL protocol (ease of recyclability/recovery/disposal) is important as an element of the circular economy. Also of interest is the potential impact on health for improper disposal	Recyclability of product & process elements	Process design calculations, LCI data	LCI databases
				Potential health risks for improper disposal of product & process elements	Chemical safety data	COSHH database, ILO International Chemicals Safety Cards database
Workers	Child labour	Assess whether the organization is employing child labour as defined by ILO conventions & to identify the nature of any child labour	Choices made in technology development/deployment may have unintended consequences regarding child labour utilisation	Potential for utilization of child labour in supply chain	Process design calculations, LCI data, COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases, Observatory of economic complexity data
	Forced Labour	Assess whether there is the use of forced labour in the organization	Choices made in technology development/deployment may have unintended consequences regarding forced labour utilisation	Potential for utilization of forced labour in supply chain	Process design calculations, LCI data, COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases, Observatory of economic complexity data

	Equal Opportunities	Assess whether there is any worker discrimination present in the organization	Choices made in technology development/deployment may have unintended consequences regarding workplace discrimination	Potential for supporting discriminatory practices in supply chain	Process design calculations, LCI data, COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases, Observatory of economic complexity data
	Worker H&S	Assess the rate of workplace incidents and prevention/management processes	It is widely understood there is a need to assess potential H&S risks in manufacturing	Risk to the H&S of workers associated with operation	ILO data on national workplace accident rate, HAZOP studies, chemical safety data	COSHH database, ILO International Chemicals Safety Cards database, ILO H&S data
Society	Public commitment to sustainability issues	Assess to what extent the organization is engaged in reducing its 'sustainability impacts' – including public & internal targets	This indicator has been changed to consider societal commitment to sustainable development	Societal & political support for sustainability initiatives that may impact the operation	IRENA energy profiles, UN SDG index scores	IRENA energy profiles, SDG index scores
	Prevention & mitigation of conflicts	Assess the organizations role in conflicts or situations that may lead to conflict (violent & non-violent)	Technologies have the potential to contribute to conflict instigation through the use of materials and labour along the supply chain	Risk of utilising of goods/materials/services from areas of conflict	LCI data, COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases, Observatory of economic complexity data
	Contribution to economic development	Assess to what extent the organization/product/service contributes to the economic development of the country	Technologies & development choices have the potential to aid (or hinder) in contributing to economic development beyond local communities	Utilisation of national supply chains over international	LCI data, COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases, Observatory of economic complexity data

Table 2 EIS: Inventory Data for CDU and Sub-processes

Item	Amine CC for 1 t CO_2/ [1,2]	Hydrogen for 1 t/h[3]	Wind per 1 kWh[4]	Solar per 1 kWh[4]	Methanol 1 t/h[3]	Polymers 1 t[5]	Mineralisation per kg carbonated block[6]
Electricity	36-202 kWh/t depending on if CHP available	52 MW	-	-	0.17 MWh	0.01 kwh/kg polyol	0.03 kWh/kg
Heat	Steam 3.7-4.4 GJ or 3.6 GJ from Nat Gas if CHP	-	-	-	0.44 MWh, saturated steam 25bar	0.05 kg steam/kg polyol = 0.14 MJ/kg	0.06 KWh/kg thermal heat
Water	Water needed for amine make up, washing and cooling recycling system used	9.4 t/h deionised water	1 kg/kWh	Average 0.9 kg/kWh to max 4 kg/kWh[7]	4.4 t/h cooling water, 0.03 t/h boiler water	1.14 kg/kg polypol cooling, 0.55 kg/kg polyol chilled water	0.11 kg/kg

Raw materials	Amines needed for capture	Pt or Pd Cathode, IrO_2 or RuO_2 anode[8]	-	Several toxic, flammable and explosive chemicals associated with manufacture	0.102 kg/h catalyst $Cu/ZnO/Al_2O_3$, 1.46 t CO_2/t MeOH, 0.199 t H_2/t MeOH	PO 0.81kh/kg polyol (0.16 less than conventional) all other feeds same as conventional, 0.23 kg CO_2/kg polyol, double metal cyanide catalyst	0.48 kg sand/kg and 0.48 kg stainless steel slag, 0.09kg CO_2/kg
Wastes	-	0.45 t/h waste water	-		0.56 t/h	-	0.09 kg waste water/kg
Emissions	1.5 kg MEA per ton CO_2 captured to flue gas, water and degradation	-	25 g CO_2/kWh minor noise issues	90 g CO_2/kwh	0.077 t/h CO_2	No delta from reference. Lower CO_2 emission.	Unknown
Land	-	Small for plant, large for electricity	44.7 acres/MW	6.1 acres/MW issues with land competition for siting solar farms	-	-	-
H&S issues	-	H_2 storage	Bird strikes	-	-	-	-

Table 3 EIS Full Impact calculation table for Methanol in 3 locations

Subcategory	**Indicator**	**Data Calculation method and Data sources**	**Scoring method**	**MeOH UK Wind**	**MeOH UK Solar**	**MeOH China Wind**	**MeOH China Solar**	**MeOH Chile Wind**	**MeOH Chile Solar**	**Justification**
Delocalisation & migration	Likelihood of forced evictions for technology implementation	Calculate land area needed (factor in electricity source if dedicated), web search for history of forced evictions/compulsory purchases etc. to factor into risk	0 = no risk 1 = low risk 2 = med risk 3 = high risk 4 = very high risk	0	0	1	2	1	1	Reasonably low risk of displacement for economic development, wind needs larger area though likely offshore. Forced eviction most prevalent in Asia followed by Latin America
Local employment	Locals directly employed due to activity	Process data & calculations, estimation from NOL for operators, local unemployment figures, average salary in	0 = numerous, above local average pay jobs created 1 = high number of jobs created	1	0	1	0	1	0	Higher job creation in solar energy than wind (x2-3 times greater per MW)

		region vs average salary of plant operator in region	2 = medium level of jobs created 3 = low level of jobs created 4 = no benefit to local pop – zero jobs							
	Locals indirectly employed due to activity	IRENA employment calculations, COMTRADE/BP to check if process inputs can be sourced locally	0= highly localized supply chain 1 = predominately local supply chain 2 = mixed location supply chain 3 = mainly international supply chain 4 = no benefit	1	1	1	1	1	1	Localised supply apart from catalysts
Access to MR	Changes to local land use	Calculate land area needed (factor in electricity source if dedicated) and consideration for how much space is available	0=minimal issues 1= low 2= moderate 3=high 4=Significant issues	1	4	2	1	2	1	China and Chile have considerable prospects for solar deployment. UK has access to large wind resources, though land for solar an issue
	Changes to local water supply & security	https://worldwater.io/ Consideration of water scarcity within the country compared to amount of water needed for production	0=minimal issues 1= low 2= moderate 3=high 4=Significant issue	2	2	1	2	2	2	China has low level of people living in water scarce areas (36%) UK and Chile are higher (46% and 52% respectively).
	Changes to local electricity supply	https://www.irena.org/Statistics/Statistical-Profiles Consideration of amount electricity needed per FU and amount of solar or wind energy produced per country	0=minimal issues with capacity (or dedicated supply) 1= low with capacity 2= moderate with capacity 3=high with capacity 4=Significant issue with capacity	2	3	1	1	4	3	Electricity demand for MeOH production is high due to water electrolysis for H2. China has least capacity issues, UK wind has greater potential for expansion. Solar & wind capacity are small in Chile, where hydro is dominant renewable energy source
	Changes to local access to material produced	https://comtrade.un.org/ Consideration of how much methanol is imported and exported	0= very high change 1= high significant change 2= moderate change 3=small change 4=no change	2	2	2	2	4	4	Chile exports large amount of methanol. UK and China import more methanol than they export so this will increase local security of supply.
Safe & Healthy Living conditions (LC)	Impact on air quality/pollution levels - production	http://wdi.worldbank.org/table/WV.3 Using the air pollution data per country and adding possible additional air pollution from process	0= no/positive impact 1 = low impact 2 = medium impact 3 = high impact 4 = very high impact	0	0	2	2	1	1	Air pollution is worst in China and best in UK. The amines from the capture process will add to local air pollution.
	Utilisation of hazardous	Consideration of the hazards created raw materials used in process, storage and	0= no impact 1 = low impact 2 = medium impact	2	2	2	2	2	2	Use of amines and H_2 (H_2 needs storage)

	substances in process	transportation of product. Use of Hazop data for materials.	3 = high impact 4 = very high impact							
Promoting social responsibility	Use of wastes and other sustainably materials	Consideration of how many raw material as sourced from waste or are sustainable	0= very high use of sustainable/wastes 1 = high use 2 = medium use 3 = low use 4 = no use/unstainable	1	1	1	1	1	1	Inputs are sustainable as renewable H_2 production is used, however electrodes use platinum group metals
	Social responsibility in supply chain	Risk of utilisation of illicit or conflict materials within supply chain https://www.usgs.gov/centers/nmic/platinum-group-metals-statistics-and-information	0= no risk 1 = low risk 2 = medium risk 3 = high risk 4 = very high risk	1	1	1	1	1	1	Platinum group metals used but sustainable reporting is common for the metals therefore sustainably producer could be chosen
Consumer health & safety	Consumer health & safety risk	Consideration as to whether product poses any consumer H&S issues. Data from COSHH	0= no risk 1 = low risk 2 = medium risk 3 = high risk 4 = very high risk	2	2	2	2	2	2	Methanol predominantly used in industry rather than by consumers, however poses acute health hazards for oral , dermal and inhalation toxicity and is highly flammable.
EOL responsibility	Recyclability of product & process elements	Consideration of raw materials, wastes and products in respect to their ability to be recycled. Consideration of ease of recycling.	0= no impact/ easily fully recyclable 1 = low impact/some issues recycling 2 = medium impact/ recycling + end of life pyrolysis/energy recovery 3 = high impact/ recycling via DAC 4 = very high impact/ cannot be recycled	3	3	3	3	3	3	Methanol is not a product able to be recycled directly is going to emit CO_2, can be recycled by air capture of CO_2
	Potential health risks for improper disposal of product & process elements	Potential impact on health, data from knowledge of process elements and product disposal.	0= no impact 1 = low impact 2 = medium impact 3 = high impact 4 = very high impact	1	1	1	1	1	1	No issues for product disposal, high use of electrolysers for H_2 = disposal of used electrodes
Child labour	Potential for utilization of child labour in supply chain	http://wdi.worldbank.org/table/2.6 Likelihood that their might be child labour occurring in supply chain and scenario country	0= no likelihood 1 = low likelihood 2 = medium likelihood 3 = high likelihood 4 = very high likelihood	0	0	0	0	1	1	Chile has low levels of child labour though these are mainly concentrated in the services and agricultural industries.
Forced labour	Potential for utilization of forced labour in supply chain	Consideration of likelihood of forced labour in supply chain and impact http://ilo.org/wcmsp5/groups/public/@dgreports/@dcomm/documents/publication/wcms_575479.pdf	0= no likelihood 1 = low likelihood 2 = medium likelihood 3 = high likelihood 4 = very high likelihood	1	1	1	1	1	1	Higher risk in Africa, Asia and Pacific. Metal catalysts likely to be sourced from Africa however quantities needed are low.

Equal Opportunities	Potential for supporting discriminatory practices in supply chain	Labour force participation rate in the country. Data from World Bank regarding employment in location.	0= no likelihood of supporting discrimination 1 = low likelihood 2 = medium likelihood 3 = high likelihood 4 = very high likelihood	0	0	1	1	0	0	UK and Chile have high levels of female employment. China has much lower levels of employment which could lead to discriminatory practice.
Worker health & safety	Worker health & safety risk	Country H&S data and consideration of process https://ilostat.ilo.org/topics/safety-and-health-at-work/	0= no impact 1 = low impact 2 = medium impact 3 = high impact 4 = very high impact	2	2	2	2	3	3	H_2 storage & transportation and possible exposure to amines are biggest issues regarding H&S. UK has a better H&S Chile. Unknown for China
Public commitment to sustainability issues		Irena Energy profiles, commitment to renewable energy targets and frequency of environmental policy http://solability.com/the-global-sustainable-competitiveness-index/the-index https://www.sdgindex.org/	0= very high 1 = high commitment 2 = medium commitment 3 =low commitment 4 = no commitment	1	1	2	2	2	2	Chile has very high renewable energy targets, but with China is lower in the Global sustainable competitiveness ranking than UK
Prevention & mitigation of conflicts	Potential for utilisation of goods/materials/services	Consideration of sources of raw materials for the process. Are these from areas with conflict or could alternative sourcing contribute to mitigation?	0= no impact 1 = low impact 2 = medium impact 3 = high impact 4 = very high impact	1	1	1	1	1	1	All countries would likely be sourcing metals externally therefore rankings similar.
Contribution to economic development	Use of local supply chain	How many raw materials can be sourced local reducing demand for imports and therefore increasing local economy.	0= very high use 1 = high use 2 = medium use 3 = low use 4 = no use	1	1	1	1	1	1	Raw materials apart from metals can all be sourced locally, only CO_2 and water required.

Table 4 EIS Full Impact calculation table for comparison of methanol, polymers and minerals via CDU in UK scenario

Subcategory	Indicator	Data Calculation method and Data sources	Scoring method – where 2 scoring methods are given, average of both scores is calculated	MeOH UK Wind	MeOH UK Solar	Polymer UK Wind	Polymer UK Solar	Mineral UK Wind	Mineral UK Solar	Justification
Delocalisation & migration	Likelihood of local forced evictions for technology implementation	Calculate land area needed (factor in electricity source if dedicated), web search for history of forced evictions/compulsory purchases etc to factor into risk	0 = no risk 1 = low risk 2 = med risk 3 = high risk 4 = very high risk	0	0	0	0	0	0	Highly unlikely in UK scenario, most land used for MeOH solar but this likely to be agricultural land
Local employment	Locals directly employed due to activity	Process data & calculations, estimation from NOL for operators, local unemployment figures, average salary in region vs average salary of plant operator in region	0 = numerous, above local average pay jobs created 1 = high number of jobs created 2 = medium level of jobs created 3 = low level of jobs created 4 = no benefit to local pop – zero jobs	1	0	3	3	3	3	Higher job creation in solar energy than wind (x2-3 times greater per MW), however polymer and minerals use much lower levels of renewable energy therefore just
	Locals indirectly employed due to activity	IRENA employment calculations,COMTRADE/BP to check if process inputs can be sourced locally	0= highly localized supply chain 1 = predominately local supply chain 2 = mixed location supply chain 3 = mainly international supply chain 4 = no benefit	1	1	1	1	0	0	Localised apart from catalysts, for mineralisation use of waste local materials
Access to MR	Changes to local land use	Calculate land area needed (factor in electricity source if dedicated) and consideration for how much space is available	0=minimal issues 1= low 2= moderate 3=high 4=Significant issues	2	4	1	1	1	1	UK has access to large offshore wind resources, though land for solar an issue. Electricity demand for MeOH highest.
	Changes to local water supply & security	https://worldwater.io/ Consideration of water scarcity within the country compared to amount of water needed for production	0=minimal issues 1= low 2= moderate 3=high 4=Significant issue	2	3	0	0	0	1	Minimal water needed for Polymers and Minerals, though solar had high water demand per MWh
	Changes to local electricity supply	https://www.irena.org/Statistics/Statistical-Profiles Consideration of amount electricity needed per FU and amount of solar or wind energy produced per country	0=minimal issues with capacity (or dedicated supply) 1= low with capacity 2= moderate with capacity 3=high with capacity 4=Significant issue with capacity	2	2	0	0	0	0	MeOH has high electricity demand due to H_2 production.
	Changes to local access to material produced	https://comtrade.un.org/ Consideration of how much methanol is imported and exported	0=very high change 1= high significant change 2= moderate change 3=small change 4=no change	2	2	3	3	4	4	More methanol is imported than exported, Polyurethane imports and exports are similar and high value, mineral imports are lower value

Safe & Healthy Living conditions (LC)	Impact on air quality/pollution levels - production	http://wdi.worldbank.org/table/WV.3 Using the air pollution data per country and adding possible additional air pollution from process	0= no/positive impact 1 = low impact 2 = medium impact 3 = high impact 4 = very high impact	0	0	0	0	1	1	Mineralisation has potential to be carbon negative technology reducing CO_2 levels
	Utilisation of hazardous substances in process	Consideration of the hazards created raw materials used in process, storage and transportation of product. Use of Hazop data for materials.	0= no impact 1 = low impact 2 = medium impact 3 = high impact 4 = very high impact	2	2	0	0	0	0	Use of amines and H_2 (H_2 needs storage) for MeOH. Much lower level of amine needed for polymers and minerals
Promoting social responsibility	Use of wastes and other sustainably materials	Consideration of how many raw material as sourced from waste or are sustainable	0= very high use of sustainable/wastes 1 = high use 2 = medium use 3 = low use 4 = no use/unstainable	1	1	2	2	0	0	Mineralisation uses wastes as feedstocks, methanol uses some platinum group metals for electrolysis, polymers use more materials that could be sourced from fossil resources, care needs to be taken to reduce this.
	Social responsibility in supply chain	Risk of utilisation of illicit or conflict materials within supply chain	0= no risk 1 = low risk 2 = medium risk 3 = high risk 4 = very high risk	1	1	1	1	0	0	Metal catalyst and electrode metals have very low possibility of being sourced illicitly or from conflict areas.
Consumer health & safety	Consumer health & safety risk	Consideration as to whether product poses any consumer H&S issues. Data from COSHH	0= no risk 1 = low risk 2 = medium risk 3 = high risk 4 = very high risk	2	2	0	0	0	0	Methanol predominantly used in industry rather than by consumers, however poses acute health hazards for oral , dermal and inhalation toxicity and is highly flammable
EOL responsibility	Recyclability of product & process elements	Consideration of raw materials, wastes and products in respect to their ability to be recycled. Consideration of ease of recycling.	0= no impact/ easily fully recyclable 1 = low impact/some issues recycling 2 = medium impact/ recycling + end of life pyrolysis/energy recovery 3 = high impact/ recycling via DAC 4 = very high impact/ cannot be recycled	3	3	2	2	0	0	Methanol is not a product able to be recycled directly is going to emit CO_2, can be recycled by air capture of CO_2. Polymers recycled until end of life. Minerals do not need recycling, though can be crushed and reused
	Potential health risks for improper disposal of product & process elements	Potential impact on health, data from knowledge of process elements and product disposal.	0= no impact 1 = low impact 2 = medium impact 3 = high impact 4 = very high impact	1	1	0	0	0	0	No issues for product disposal, high use of electrolysers for H_2 = disposal of used electrodes
Child labour	Potential for utilization of child labour in supply chain	http://wdi.worldbank.org/table/2.6 Likelihood that their might be child labour occurring in supply chain and scenario country	0= no likelihood 1 = low likelihood 2 = medium likelihood 3 = high likelihood 4 = very high likelihood	1	1	0	0	0	0	MeOH uses high level of catalyst/rare metals which can be sourced from areas using child labour

Forced labour	Potential for utilization of forced labour in supply chain	https://ilostat.ilo.org/ http://ilo.org/wcmsp5/groups/public/@dgreports/@dcomm/documents/publication/wcms_575479.pdf	0= no likelihood 1 = low likelihood 2 = medium likelihood 3 = high likelihood 4 = very high likelihood	1	1	0	0	0	0	MeOH uses high level of catalyst/rare metals which can be sourced from areas using forced labour
Equal Opportunities	Potential for supporting discriminatory practices in supply chain	Labour force participation rate in the country. Data from World Bank regarding employment in location.	0= no likelihood 1 = low likelihood 2 = medium likelihood 3 = high likelihood 4 = very high likelihood	1	1	1	1	0	0	Not likely in UK however could play a factor within supply chain of metals for catalysts
Worker health & safety	Worker health & safety risk	Country H&S data and consideration of process https://ilostat.ilo.org/topics/safety-and-health-at-work/	0= no impact 1 = low impact 2 = medium impact 3 = high impact 4 = very high impact	2	2	1	1	1	1	H_2 storage & transportation and possible exposure to amines are biggest issues regarding H&S for MeOH.
Public commitment to sustainability issues		Irena Energy profiles, commitment to renewable energy targets and frequency of environmental policy http://solability.com/the-global-sustainable-competitiveness-index/the-index https://www.sdgindex.org/	0= very high 1 = high commitment 2 = medium commitment 3 = low commitment 4 = no commitment	1	1	2	2	1	1	MeOH could be included in renewable energy targets and help with grid balancing, mineralisation can count towards net zero targets as a carbon dioxide sink
Prevention & mitigation of conflicts	Potential for utilisation of goods/materials /services	Consideration of sources of raw materials for the process. Are these from areas with conflict or could alternative sourcing contribute to mitigation?	0= no impact 1 = low impact 2 = medium impact 3 = high impact 4 = very high impact	1	1	0	0	0	0	High level of catalyst used for MeOH which may be sourced from unstable regions.
Contribution to economic development	Use of local supply chain	How many raw materials can be sourced local reducing demand for imports and therefore increasing local economy.	0= very high use 1 = high use 2 = medium use 3 = low use 4 = no use	1	1	2	2	0	0	Mineralisation recycles waste products, MeOH predominantly local supply chain though catalysts not local, PO may be externally sourced for polymers

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REVIEW
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The Social Acceptance of Carbon Dioxide Utilisation: A Review and Research Agenda

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CO_2 utilisation technologies—also called carbon dioxide utilisation (CDU) and carbon capture and utilisation (CCU)—convert CO_2 *via* physical, chemical, or biological processes into carbon-based products. CO_2 utilisation technologies are viewed as a means of helping to address climate change and broadening the raw material base for commodities that can be sold to generate economic revenue. However, while technical research and development into the feasibility of CO_2 utilisation options are accelerating rapidly; at present, there has been limited research into the social acceptance of the technology and CO_2-derived products. This review article outlines and explores three key dimensions of social acceptance (i.e., socio-political, market, and community acceptance) pertaining to innovation within CO_2 utilisation. The article highlights the importance of considering issues of social acceptance as an aspect of the research, development, demonstration, and deployment process for CO_2 utilisation and explores how key stakeholders operating on each dimension might affect the innovation pathways, investment, and siting decisions relating to CO_2 utilisation facilities and CO_2-derived products. Beyond providing a state-of-the-art review of current research into the social acceptance of CO_2 utilisation, this article also outlines an agenda for future research in the field.

Keywords: carbon dioxide utilisation, carbon capture and utilisation, social acceptance, public perception, review

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INTRODUCTION

Carbon dioxide utilisation (CO_2 utilisation or CDU) technologies—also called Carbon Capture and Utilisation (CCU) technologies—utilise CO_2 as a valuable carbon resource. CO_2 utilisation technologies can be defined as converting CO_2 *via* physical, chemical, or biological processes into carbon-based products (see **Figure 1**). Thus, these technologies can be thought of as a new synthetic carbon cycle, which uses and releases CO_2 back to the atmosphere or sequesters it in products. By sequestering CO_2 and/or reducing the direct reliance on extracted fossil fuels as a carbon-feedstock for the manufacture of commodity products, CO_2 utilisation technologies are seen as a means of helping to mitigate climate change, while simultaneously creating useful, saleable products that can potentially offset the costs associated with the capture and/conversion processes (Styring et al., 2014).

CO_2 utilisation is often directly compared and contrasted with Carbon Capture and Storage (CCS); however, they are two distinct technology paths and so it is necessary to treat and evaluate these technologies individually, especially with regard to environmental policy targets (Bruhn et al., 2016). Specifically, CCS is a CO_2 mitigation strategy; its objective is to deal with large volumes of CO_2

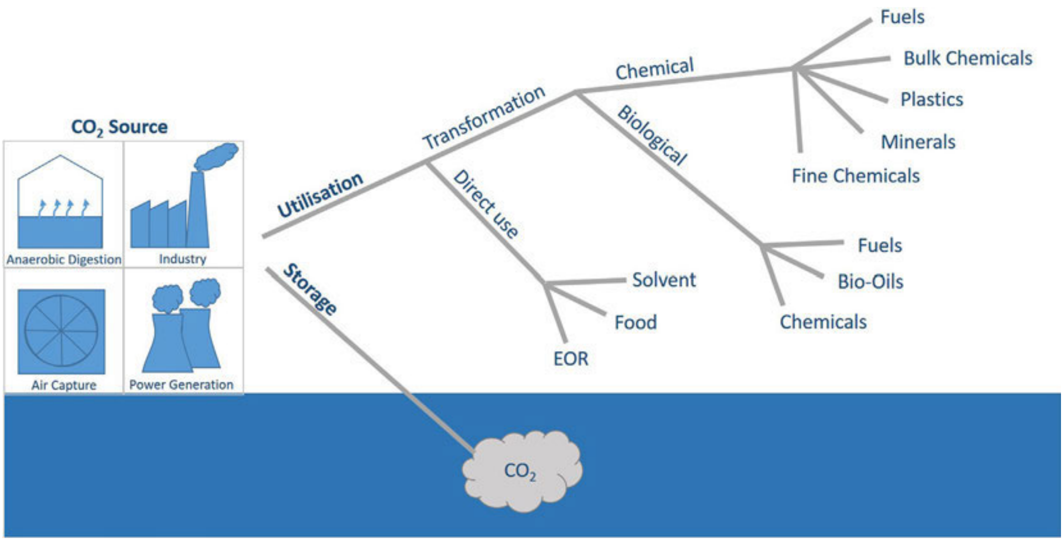

FIGURE 1 | Carbon dioxide storage and utilisation options. Carbon dioxide from point source emitters (e.g., fossil fuel power generation or other large industrial emitters) or *via* direct air capture or biological processes can be geologically stored (*via* carbon capture and storage) or used. Use of CO_2 can be direct (e.g., for use in "enhanced oil recovery") or the captured CO_2 can be transformed *via* chemical or biological processes for use as a carbon feedstock (e.g., for the manufacture of fuels, chemicals, plastics, etc.).

emissions by capturing and sequestering the gas in geological formations for periods of hundreds of years (Intergovernmental Panel on Climate Change, 2005). CO_2 utilisation on the other hand uses CO_2 as a feedstock for the creation of new, value-add products; it can promote sustainability and a circular economy, encourage industrial symbiosis and economic growth and enable the storage of renewable energy. Thus, while both technologies "capture" CO_2, the subsequent treatment of the gas is very different.

While the majority of CO_2 utilisation options remain at low technology readiness levels (or TRLs) (Wilson et al., 2015), some CO_2-derived products are beginning to emerge on to the market [e.g., synthetic methane (or "e-gas") produced by Audi; polyols manufactured by Covestro and Novomer (under the trade names Cardyon and Converge, respectively) and construction aggregates from the accelerated mineralisation of waste ashes by Carbon8 Aggregates]. Importantly, as the commercialization of products and processes continues, there will be an associated growth in the interactions that a diversity of social stakeholders (including policy-makers, businesses, the general public, etc.) will share with CO_2 utilisation facilities and products. For example, consumer purchase decisions may help to determine whether products containing CO_2 succeed in a competitive marketplace. Thus, developing a firm understanding of the factors and actors likely to shape the "social acceptance" of CO_2 utilisation should be a priority for research. Interestingly, however, to date there has been very little systematic research in this area (Jones et al., 2015). This is a situation that contrasts markedly with the rich literature that now exists relating to the key factors and actors likely to govern the "social acceptance" of CCS technologies (see, e.g., L'Orange Seigo et al., 2014).

Within the current article, we directly address this knowledge gap by first outlining a key framework for conceptualizing the social acceptance of technological innovation, before summarizing and synthesising the findings from the extant literature pertaining to the social acceptance of CO_2 utilisation technologies. Where relevant, inferences about the factors and actors likely to shape the future commercial success of CO_2 utilisation are also made. We end by outlining a research agenda for future academic inquiry into the social acceptance of CO_2 utilisation technologies; highlighting the key questions that need addressing and the methodological considerations that should be kept in mind in the pursuit of such research.

THE IMPORTANCE OF SOCIAL ACCEPTANCE

Social acceptance, or the extent to which an innovation (e.g., a policy, technology) is endorsed or rejected by key social actors (e.g., politicians, financiers, and publics), is recognised as being necessary for the successful introduction and commercial success of such innovation (e.g., Wüstenhagen et al., 2007; Perlaviciute and Steg, 2014; Upham et al., 2015). This is particularly the case within Western democracies, where policy or institutional change typically requires the support of individuals and communities (Peterson et al., 2015). Indeed, there are a growing number of examples of where failures to appropriately engage with, assess and accommodate the opinions of key social actors at a general, regional and/or local level has led to delays or curtailments to the introduction of innovations (e.g., GM technology, Horlick-Jones et al., 2006; renewable energy technologies, Devine-Wright, 2011).

Formal investigations into the social acceptance of new technologies date back to the 1980s where, at the time, a growing recognition of the governing influence that myriad stakeholders could exert upon the path of technological innovation, investment, and deployment led to a realisation that understanding (and influencing) the factors affecting the success of such innovation demanded more than a simple assessment of general public opinion (Wüstenhagen et al., 2007; Fournis and Fortin, 2017). Since then, respect for the importance of understanding and addressing the issue of social acceptance (and social acceptability[1]) of technologies has grown rapidly (Fournis and Fortin, 2017).

Logically, a diversity of frameworks of social acceptance have followed—stemming from a number of psychological, sociological, and technical perspectives—aiming to provided working definitions of "acceptance" and showcase the important dimensions and stakeholders (and their associated relationships) that underpin whether or not technological or policy innovations are accepted (e.g., Szarka, 2007; Wüstenhagen et al., 2007; Shove, 2010; Huijts et al., 2012; Upham et al., 2015).

For example, Huijts and colleagues (2012), from a *psychological* perspective, propose a comprehensive framework of *public* acceptance of sustainable energy technologies (SETs). This framework considers an individual's intentions to support or oppose SETs to be a product of their attitudes, personal norms, perceived behavioural control, and subjective norms; concepts which are in turn predicted by other factors (e.g., perceived costs, risks, and benefits of the SET). However, while Huijts et al.'s (Huijts et al., 2012) framework provides a helpful take on the issues of *public* acceptance (see also Gupta et al., 2012), it fails to acknowledge that the *social* acceptance of innovation is governed by manifold social stakeholders (including but not limited to publics) working at multiple levels (macro, meso, and micro). Furthermore, the model cannot accommodate the epistemological differences of research stemming from other disciplinary perspectives (e.g., sociological accounts of technology acceptance, e.g., Shove, 2010).

With this in mind, the introduction to the social acceptance of CO_2 utilisation within the current article is structured in accordance with Wüstenhagen et al.'s (Wüstenhagen et al., 2007) "triangle of social acceptance" (see also Wolsink, 2012); a broader, conceptual framework, which characterizes the three levels of acceptance typically thought to shape the fate of technological and policy innovation (Upham et al., 2015). According to this framework, social acceptance of innovation to be the product of three dimensions: socio-political, market, and community acceptance (see **Figure 2**). While originally designed to profile the factors and actors influencing the social acceptance of renewable energy policy and technologies; the "triangle" framework has been applied within other policy domains, such as waste management and climate change adaptation (Wolsink, 2010).

According to Wüstenhagen and colleagues (2007), *socio-political acceptance* refers to the acceptance of technologies

FIGURE 2 | The "Triangle of Social Acceptance." The "triangle" framework proposes that the social acceptance of policy and technology innovation is determined by the opinions and actions of stakeholders operating on three dimensions (i.e., socio-political, market, and community acceptance). The figure is adapted from Wüstenhagen et al. (2007) and is reproduced with the permission of the copyright holder.

and policies at the broadest, most general level by major social actors (e.g., the general public, policy-makers). By contrast, *market acceptance* is more specific and integrates considerations of the diffusion of innovation among consumers and the interactions and investment decisions of technology investors (e.g., the chemical industry or plant engineers); operating as both competitive and collaborative entities within both national and/or multinational contexts. Finally, *community acceptance* is the acceptance of specific projects at a local level by stakeholders (particularly residents and local authorities) living proximal to the development. It is at this level that trust in decision-makers and perceptions of procedural and distributive justice (i.e., the extent to which decision-making processes and the distribution of risk and benefits are thought to be fair and equitable) are believed to shape the ability to deploy specified projects.

According to the "triangle" framework, the three dimensions of social acceptance are often interrelated (i.e., the decisions made by key actors on one dimension can have ramifications for acceptance of innovation on the other dimensions). For example, failures to institutionalize frameworks to promote market and community acceptance at the socio-political level (e.g., procurement mechanisms, decision-making protocols) can mean that general support for a technology may fail to translate into business and consumer investment and/or local support for the construction of specified projects. Similarly, it is possible that existing market path-dependencies can provide inertia to the adoption of technological innovations endorsed at a socio-political and/or community level. Further, it is the differences in acceptance recorded at the socio-political (i.e., general) and community (i.e., local) level that has given rise to extensive research into so-called NIMBYism (not in my backyard, e.g., van der Horst, 2007; Jones and Eiser, 2010) and ongoing debates around the benefits and drawbacks of devolved versus centralised decision making (e.g., Bouffard and Kirschen, 2008).

While some researchers have critiqued the general concept of "social acceptance" (e.g., Batel et al., 2013) or have criticized Wüstenhagen et al.'s framework for failing to fully and explicitly

[1]There is ambigu ty around the use of the terms "acceptance" and "acceptability." While often used interchangeably they are noted to be different concepts (Fournis and Fortin, 2017). We favour use the term "acceptance" within the current article, not only because it is used by the "triangle" framework (i.e. the conceptual framework around which we structure the current review) but t is also a term that simplistically refers to whether something is accepted or not, as opposed to mapping to more complex, dynamic and hierarchical discussions of collective choice (Szarka, 2007).

define the assumptions upon which it rests and/or recognize the complexities around the stakeholder relationships it identifies (Fournis and Fortin, 2017); the "triangle" framework is widely cited and provides a good basis from which to foster a global understanding of the people and processes that are likely to determine whether or not innovations are socially accepted and therefore succeed or fail. Moreover, the proposed key dimensions of acceptance (i.e., socio-political, community, and market acceptance) have been confirmed by other commentators (e.g., Upham et al., 2015).

In the following sections, then, we explore each of the three dimensions of the "triangle" in turn; outlining the factors and actors that are likely to influence decisions about the acceptance of CO_2 utilisation (both in general and with regard to specific products or siting of facilities) and summarising the nature and findings of any extant research that has been conducted. The review ends by proposing a number of key research questions that we feel should form the basis of future investigation in the field.

THE SOCIAL ACCEPTANCE OF CO_2 UTILISATION

Socio-Political Acceptance

General socio-political support for (or rejection of) a given innovation can fundamentally shape its success. There are numerous examples of where failures to secure appropriate socio-political support for a technology has delayed or curtailed its introduction. This is exemplified, for example, by resistance to the introduction of E10 (10% ethanol) automotive fuel in a number of countries due to concerns about its effect on fuel prices and the perceived risks it poses to the operation of some older vehicles (Hauke, 2014). Also, the introduction of CCS technologies in some countries (e.g., Germany) has been stymied by a strong resistance to the concept among stakeholders and the general public (Brunsting et al., 2011; L'Orange Seigo et al., 2014). The following section outlines some of the key factors and actors at the socio-political level that are likely to shape the development and deployment of CO_2 utilisation technologies.

The primary driver behind socio-political interest in CO_2 utilisation to date has been climate change mitigation. This interest has arisen in response to national and international legislation regarding greenhouse gas emissions (e.g., European Union Emission Trading System, the Renewable Energy Directive, and the Fuel Quality Directive). Policy-makers are concerned with reducing the "carbon footprint" of their individual countries and industrial emitters are concerned with the possibility of economic penalties that could result from their emissions. These growing pressures (alongside other concerns, e.g., ensuring the security of raw resources) have led to accelerated innovation in technology and policy relating to CO_2 utilisation.

Within this space, one can assume that the views of societal opinion leaders and industrial-sector decision-makers about whether or not to invest in CO_2 utilisation (or particular technology or product options)—shaped by, for example, individual expertise, personal opinions, "bottom line" considerations, policy support, and media coverage (e.g., Kepplinger, 2007)—will influence the broader socio-political acceptance of CO_2 utilisation and, hence, investment and development of the technology. However, while there have been informal efforts to engage with and network interested actors (e.g., by SCOT and CO2Chem)[2,3] to date there has been no formal systematic research in this area. As such, we argue that formal stakeholder analysis (e.g., Hemmati, 2002; Roloff, 2008; Freeman, 2010) in order to identify the key industrial (and other) stakeholders within the sector (both emitters and users) and to establish their motivations and requirements for investment should be a priority. This will identify levers, synergies, and courses of action which can be undertaken from both a policy and industrial perspective.

Public funding schemes and research-programme investment are a key means by which synergies can be formed and innovation encouraged. They provide a high level of facilitation for innovative technologies and, in turn, can positively steer internal decision making processes. There are currently around 34 governmental programmes for research into CO_2 utilisation worldwide.[4] The pre-requisites for the establishment of such programmes are manifold but appear to include, for instance, the existence of a strong chemical industry (e.g., Germany, Netherlands, Korea), the existence of an extractive oil or gas industry that has an interest in "enhanced recovery" applications (e.g., Canada, USA), or, in countries that plan to continue to use fossil fuel resources for their energy supply, the existence of coal-fired plants aiming at installing "Clean Coal" systems (e.g., China) (Olfe-Kräutlein et al., 2016, for a full outline of current programmes).

Interestingly, there often appears to be a disjunction between what developers see as the primary purpose of CO_2 utilisation technology and the motivations driving governmental research-programme investment in the sector. That is, while industrial and academic actors involved in the development of CO_2 utilisation technologies emphasise the fairly limited contribution that such technologies can make to climate change mitigation efforts (e.g., due to a dependency on the availability of renewable energy, see e.g., Bringezu, 2014); research programme investment is often rooted in this "climate change mitigation" context. There are evident questions as to the long-term consequences that any difference in the purported versus perceived rationale for CO_2 utilisation might have for future public investment in the sector. Arguably, policies for investment need to evolve and realign to recognise the wider use-value of CO_2 utilisation technologies (e.g., contributions to the sustainability and breadth of the raw material base of a country); this is something which has been recognised by the German government through their CO_2Plus initiative (funded as part of the broader "Green Economy" initiative).[5]

Relatedly, there are questions as to how wider socio-political confidence in CO_2 utilisation might be affected by any misalignment in the perceived versus stated rationales for investment in the technology. For example, the way in which CO_2 utilisation is

[2] http://www.scotproject.org/
[3] http://co2chem.co.uk/
[4] http://database.scotproject.org/
[5] https://www.ptj.de/co2plus

publicly "framed" might have consequences for support among a number of socio-political actors including, notably, the general public. Indeed, not only does research into framing reveal how the manner in which technological innovation is presented can exert a large impact on public opinion (e.g., Chong and Druckman, 2007; Jones et al., 2012; de Vries et al., 2016) but also that perceived discrepancies between the purported and perceived rationale for investment in technology can negatively affect public trust (e.g., Terwel et al., 2011).

While the views of the general public are a known determinant of the success of technological and policy innovation; research into the public acceptance of CO_2 utilisation is currently sparse. This reflects the early technology readiness level of many CO_2 utilisation options and low level of public awareness of the technology at the present time. The few studies that do exist have tended to use discursive methods (e.g., focus groups, semi-structured interviews) to assess initial understanding of the technology and gain initial insights into the factors that might underpin acceptance (e.g., Jones et al., 2014, 2016; van Heek et al., 2017a,b). That said, recently, details of findings from larger scale surveys are beginning to emerge (Perdan et al., 2017). In combination with formative research into the opinions of selected experts (Olfe-Kräutlein et al., 2016; van Heek et al., 2017a,b) and *via* monitoring participation in stakeholder discourse events (Olfe-Kräutlein et al., 2016), a picture of public perceptions of CO_2 utilisation technologies (and how these map to and/or diverge from those of experts) is beginning to build.

The results of these studies generally confirm that awareness of CO_2 utilisation is currently very low and while there is some scepticism about the long-term environmental benefits of the technology, there is tentative overall support for the concept as a "bridging technology" in the fight against climate change (Jones et al., 2015, 2016). This support is, however, strongly caveated by people's self-professed lack of knowledge of the technology, questions over the techno-economic feasibility of the processes and uncertainty over the societal consequences of investment in the technology. For example, some people question whether or not investment in CO_2 utilisation could detract from investment in more preferable low-carbon technologies (e.g., renewables) or conflict with broader sustainability goals (e.g., CO_2 utilisation is seen by some as being predicated on the continued use of fossil fuels) (e.g., Jones et al., 2016). A summary of the formative research that has been conducted to date into general public perceptions of CO_2 utilisation can be found in **Table 1**.

To some extent, the results of this initial research into public perceptions can be seen to be a product of the pro-environmental focus of the framing used to introduce the technology to participants. The power that such framing is likely to have on opinions is likely to be further enhanced by the novelty and unfamiliarity of the technology (Druckman and Bolsen, 2011). An obvious starting point for future research in this area, then, is to investigate the role that different framing of CO_2 utilisation (e.g., to focus on alternative costs, benefits, or risks) might have on public opinion. Moreover, there are related questions pertaining to how emerging mental models and/or affective evaluations of CO_2 shape how communications regarding CO_2 utilisation are perceived among lay-publics (e.g., Montijn-Dorgelo and Midden, 2008).

TABLE 1 | Summary of the key studies conducted into emerging perceptions of CO_2 utilisation technologies and product options.

Study (location)	Year	Aim
Jones et al. (2014) (UK)	2014	Qualitative focus group study with follow-up information-choice questionnaire, designed to (a) test a methodology for assessing public perceptions of CO_2 utilisation and (b) elucidate new understanding of people's attitudes to the technology
Jones et al. (2015) (UK)	2015	Qualitative focus group study (with questionnaire), building on 2014 study, designed to investigate and assess emerging lay public perception of CO_2 utilisation among groups of adults and high school students
Olfe-Kräutlein et al. (2016) (Germany)	2016	Semi-structured interview and participant observation study, designed to explore the potential for and barriers to communication about CO_2 utilisation. Study provides (a) an analysis of expert and other stakeholder perspectives and (b) strategic comments for future communications regarding CO_2 utilisation
Jones et al. (2016) (UK/Germany)	2016	Focus group study (with questionnaire), designed to investigate and compare and contrast laypeople's opinions towards CO_2 utilisation technologies in the UK and Germany
Arning et al. (2017) (Germany)	2017	Qualitative focus group and online survey study, designed to (a) conceptualize CO_2-utilisation risk perception; (b) evaluate the relationship between risk perception and product acceptance and (c) provide a breakdown of the factors affecting responses within different user-groups
van Heek et al. (2017a) (Germany)	2017	Qualitative interview study designed to assess acceptance of different CO_2-derived plastic products. Study compares layperson and scientific expert attitudes and perspectives
van Heek et al. (2017b) (Germany)	2017	Combination of qualitative and quantitative methods with the aim to deliver insights into acceptance drivers and barriers connected to CO_2 utilisation technology
Perdan et al. (2017) (UK)	2017	Quantitative survey of 1213 UK adults, designed to establish the extent of people's awareness and acceptance of CO_2 utilisation and to elicit the importance they put on different sustainability issues relevant to the technology

Full references for the studies can be found in the reference section.

One of the mooted benefits of research into public perception is that the knowledge gleaned from such activity could be used in order to inform public engagement and communication materials by helping to identify possible misperceptions and/or key concerns and benefits. Parallel research conducted into public perceptions of carbon capture and storage (CCS), for example, has been used to provide a scientifically sound basis for communication relating to this technology (Brunsting et al., 2011). Intriguingly, early evidence shows that the conceptual relatedness of CCS to CO_2 utilisation (and the fact it is often called CCU) could have implications for the public acceptance of CO_2 utilisation technology (Jones et al., 2016), particularly in countries or contexts where CCS has proven to be controversial and/or rejected at a socio-political level (e.g., Germany) (L'Orange Seigo et al., 2014).

A key shaper of public opinion at the socio-political level is the media. Media coverage (e.g., news reports) continues to play an important role in spreading information and raising awareness about technological innovation (Hampel and Zwick, 2016; Weitze and Weingart, 2016). While a full analysis of media coverage of CO_2 utilisation technologies has yet to be published (and remains a priority for future research), informal analysis indicates that media coverage at present tends to be positive. Although, negative connotations have been reported in some contexts where CO_2 utilisation is considered alongside CCS technologies (Bruhn et al., 2016). A number of interesting questions exist regarding how media coverage will develop and shape public opinion going forward. For example, there are questions as to whether or not media exaggeration of the purported benefits of CO_2 utilisation might raise false expectations among the general public and other socio-political stakeholders (Olfe-Kräutlein et al., 2016).

In summary, how technological innovation is received and responded to at the socio-political level has key implications for investment decisions and public support. The studies that have been conducted to date have provided first insight into some of the factors likely to govern acceptance at a socio-political level. These indicators should now serve as a starting point for more comprehensive research in the field. An option for such research—and one that would allow for a wider precis of the key non-technical factors and actors likely to foster acceptance or rejection of CO_2 utilisation at this level—is to use a multi-stakeholder approach (e.g., Freeman, 2004, 2010). This approach would allow for a wider and more diverse group of stakeholders to participate in the dialogue about the future of CO_2 utilisation; as well as helping to highlight the dynamics of decision making regarding acceptance at the socio-political level.

Market Acceptance

Wüstenhagen et al. (2007), p. 2685 define market acceptance as *"…the process of market adoption of an innovation"* and examine it in regard to acceptance among consumers, investors, and intra-firm actors. In this market perspective, the decision to accept or reject an innovation is based on *diffusion theory* (Rogers, 1995). Diffusion theory separates the uptake of innovation into five steps: (1) knowledge, (2) persuasion, (3) decision, (4) implementation, and (5) confirmation (see **Figure 3**). The success of diffusion is assessed as *"the number of individuals who adopt a new idea in a specified period"* (Rogers, 1995, p. 206). This measure is influenced by a variety of factors, including the perceived attributes of the innovation, the type of innovation decision and the communication channels available (Rogers, 1995). Consequently, for any group of market actors (consumers, investors, and intra-firm actors) these factors should be considered to better understand the adoption process steps and the resulting acceptance or rejection of an innovation. In the following section, we use diffusion theory as a lens to explore the factors that might affect the market acceptance of CO_2 utilisation technologies among consumers, investors, and intra-firm actors.

Consumers

To date, limited studies have focused specifically on consumer acceptance of CO_2-derived products. The current exceptions

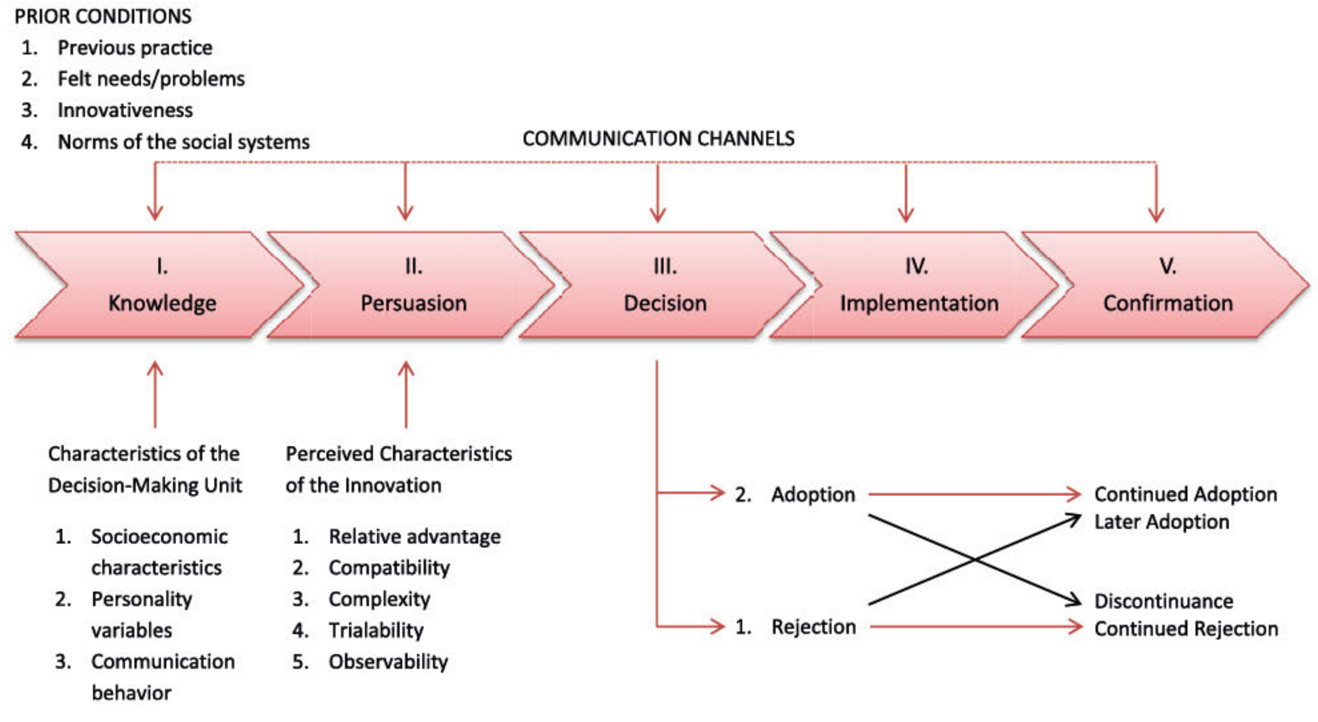

FIGURE 3 | A model of stages in the innovation-decision process. According to the model, adoption or rejection of innovation proceeds through five consecutive stages. Source: Rogers (1995), p. 165. This is an adapted version of the original figure that is reproduced with the permission of the copyright holder.

include two small qualitative studies that have focused on assessing potential consumer perceptions of CO_2-derived mattresses and plastics (Arning et al., 2017; van Heek et al., 2017a,b). Both studies reveal that the risk is deemed to be relatively low and that people tend to have positive perceptions of the products. However, while these findings are encouraging for proponents of CO_2 utilisation (e.g., investors); as both studies asked people to consider the purchase of hypothetical (rather than actual) products, there are limitations to the conclusions that can be derived regarding actual real-world consumer acceptance. As more "real" CO_2-derived consumer products reach the marketplace, it will be possible to analyse the specific effects of how, for instance, advertising, product pricing, and labelling will affect purchasing behaviour. Presently, though, learning more about the processes by which consumer opinions are liable to be formed and shaped—particularly prior to the decision to adopt or reject an innovation—is essential.

In most cases, materials derived from CO_2 utilisation will be retailed to intermediaries (e.g., product manufacturers or distributers) rather than directly to end-consumers. It is currently unclear to what extent the final retailers of consumer goods will seek to label their products as being "CO_2-derived" or with other possible messages in attempt to gain competitive market advantage (Olfe-Kräutlein et al., 2016). While there are open questions as to whether certain consumers will accept or reject CO_2-derived products on principle (e.g., irrespective of labelling or advertising); there are particularly interesting questions relating to how end users will respond in those cases where products *are* explicitly marketed as CO_2 derived. It is in these cases where the opinions of consumers will exert a particularly strong influence on the ultimate success or failure of the product(s) in question.

According to diffusion theory, because few CO_2-derived products are available to consumers on the open market and so limited numbers of consumers have ever had to face the explicit decision for or against buying a CO_2-derived product; the majority of end consumers can be considered as either having no exposure to such products or, at most, as being early in the *knowledge* stage of the model.

Perception of an innovation at the *knowledge* stage is shaped strongly by the characteristics of the socioeconomic system the consumers are part of, the communication behaviours relating to the innovation and consumers' individual attitudes (see **Figure 3**). While learning of the existence of an innovation can provide a basis for its later adoption; whether or not consumers develop this knowledge is strongly shaped by their values, beliefs, and attitudes (Rogers, 1995). For instance, consumers are more likely to seek out information on CO_2-derived products if such products are deemed to gel with their extant belief systems (e.g., if such products are seen as being congruent with their aspirations to live more sustainably).

At present, there are questions regarding the adequacy of the information that is available to consumers regarding CO_2 utilisation (and more specifically CO_2-derived products) in order to develop an informed understanding at the knowledge stage. Much of the information on the nature of CO_2 utilisation (e.g., its consequences, advantages, disadvantages) remains in scientific publications that are inaccessible to most consumers. Moreover, while all companies distribute communication materials to their own customers, the current efforts largely target at business customers since most CO_2-derived products are intermediates. The research community is thus increasingly aware of a need for neutral and evidence-based communication about CO_2 utilisation innovations for a broader public; information that is aimed at improving the base knowledge of potential future consumers—for some existing examples, see Olfe-Kräutlein et al. (2014) and Krämer et al. (2015).

Once knowledge of an innovation has developed, the *persuasion* stage of Rogers's (Rogers, 1995) model becomes relevant. Whether or not efforts to persuade people regarding an innovation translates to the decision to adopt (or reject) it is strongly influenced by the communicated characteristics of the innovation, e.g., the relative advantage the innovation will afford consumers (i.e., how useful it will be) and the perceived compatibility of the innovation with existing lifestyle practices (see **Figure 3**).[6] The decision over how CO_2-derived products are promoted to consumers ultimately rests with the producers and/or retailers consumer goods. As such, their marketing decisions about which product characteristics are emphasised will strongly influence how a product is received and whether or not it is later adopted or rejected.

Investors

In the context of CO_2 utilisation, investors include public and private R&D funding programs (aiming to promote the general development and implementation of the technologies) and private companies that see a need to capture and/or use CO_2 (e.g., large CO_2 emitters, the chemical industry). In contrast to end-consumers, investors are currently significant market actors; however, decision making at the level of investors is usually a confidential and non-public process. While the *knowledge* stage in investment decision making is generally professionalised, it is nevertheless influenced by the characteristics of the decision making unit (e.g., a profit-focused hedge fund will set different preferences than a welfare-oriented public investor.) Whether an investor is then *persuaded* to invest in CO_2 utilisation is likely to be rationally driven by strategic motives (such as the optimisation of profits or other desired KPIs) and, hence, progression through the latter stages of the diffusion model (decision, implementation, and confirmation) will depend largely on the defined targets and measurable outcomes of the investment.

While information on specific investment decisions is likely to remain largely confidential, it is nevertheless recommended to conduct research into the factors and actors driving these investment decisions. There are a few studies focussed on start-up companies (e.g., Zimmerman and Kant, 2016) or public investments (e.g., Olfe-Kräutlein et al., 2016), but a more detailed and systematic analysis of acceptance issues among investors would be beneficial. There is a further need for research into future path dependencies, for example, relating to infrastructure decisions and interfaces with the socio-political system (e.g., relevant regulation and frameworks) in order to better understand and

[6] Similar constructs are recognised in other key models of technology acceptance (e.g. the Technology Acceptance Model, e.g. Venkatesh and Davis, 2000).

improve investment security for investors. While formative studies that touch upon some of the issues pertinent to investment decisions have been published (e.g., Bringezu, 2014; Wilson et al., 2015; Naims, 2016; Piria et al., 2016), there is need to continuously review and update these according to the evolving expectations of investors and changing regulatory and policy environments.

Crucially, there is a role for the academic community in providing evidence-based support for investors in their process of decision making. These are studies that evaluate the potential and risk of different CO_2 utilisation innovations from an ecologic, economic and/or societal perspective; providing insight into the suitability and acceptability of different technologies in various future scenarios. Helpfully, the first of such studies, which not only largely focus on the environmental aspects and life cycle assessment of CO_2 utilization (e.g., Bennett et al., 2014; von der Assen and Bardow, 2014; von der Assen et al., 2016) but also with regard to the circular economy (e.g., Styring et al., 2011; Bringezu, 2014) and socioeconomic context (e.g., Naims, 2016; Olfe-Kräutlein et al., 2016) have now been published. However, as with the research into path dependencies, there will be a need for further and/or updated studies as new technologies and markets develop.

Intra-Firm Actors

Intra-firm actors are the individuals (e.g., developers, managers) or groups of individuals (e.g., departments, boards) within a company who will also play a major role with regard to acceptance and diffusion of CO_2 utilisation technologies and products. Research indicates that firms with a proactive environmental strategy tend to be more likely to invest in R&D, technology, and human resources to develop their capabilities, even in uncertain business environments (Aragón-Correa and Sharma, 2003). Thus, it can be assumed that environmentally proactive firms, in addition to those with a comfortable competitive position, are more likely to advance the development and introduction of CO_2 utilisation in comparison to those with more tentative innovation strategies and/or a weaker market position.

Within organisations, so-called "change agents" play an integral role in shaping the path of innovation. Change agents act through all stages of the diffusion process; in the best cases outlining the need for and increasing knowledge of innovations, before promoting the favourable characteristics of an innovation and expediting decision-making processes (Rogers, 1995). Consequently, the abilities of individual change agents, alongside the support systems provided to them within firms and the firms willingness and/or ability to shift extant intra-firm path dependencies (e.g., Alänge et al., 1998), will play a crucial role for the acceptance and diffusion at the intra-firm level.

At the current time, the principal intra-firm change agents for innovation in CO_2 utilisation are technically trained R&D professionals, project managers and/or business development managers. Currently, very little is known about how these individuals are operating within firms to shape the agenda for CO_2 utilisation and the development, use and/or marketing of CO_2-derived products. For example, what barriers do they face to implementing their ideas and how successful are they in communicating the need for change to their managers?

In sum, a number of factors and actors stand to shape the market acceptance of CO_2 utilisation technologies and/or CO_2-derived products. While investors are already significant actors in this arena, the first studies into their role and behaviour are ongoing and so only speculative conclusions can be drawn as to the processes driving their decisions to invest. Furthermore, while intra-firm environments and actors (e.g., change agents) are known to shape the uptake and diffusion of innovation; first studies in this field are also ongoing. Further attempts to assess their role for the diffusion and intra-firm acceptance of CO_2 utilisation will be useful. Also, formal investigations into the nature of decision making within firms seeking to invest in the CO_2 utilisation sector remains a priority for future research.

Similarly, while there is emerging intelligence on consumer attitudes towards CO_2-derived products, there are currently significant limitations to this research. To the extent that (a) there will be increased number of CO_2-derived products available to consumers in the future and (b) efforts will be made to gain competitive market advantage by communicating the source of carbon within these products, there needs to be increased research focus on the antecedents of consumer acceptance.

Community Acceptance

"Community acceptance" refers to "*…the specific acceptance of siting decisions and […] projects by local stakeholders, particularly residents and local authorities*" (Wüstenhagen et al., 2007, p. 2685). Thus, according to Wüstenhagen and colleagues (2007), this dimension is the most specific dimension of acceptance and refers to the rejection or acceptance of particular facilities or projects within geographically defined "host" communities (see also Sovacool and Ratan, 2012).

While one could choose to debate this relatively narrow definition of community—e.g., one could seek to define "community acceptance" more liberally so as to recognise that "non-local" stakeholders (e.g., global NGOs) and "communities of interest" can still exert influence over the fate of specific projects (Young, 1986; Walker and Devine-Wright, 2008)—it is certainly the case that the opposition or support received for specified projects at a local level is a key contributor to their success or failure (e.g., Devine-Wright, 2011).

Social scientific research has revealed a considerable amount about the factors likely to affect community acceptance of any array of (proposed) industrial and/or other facilities. This research has not only registered the differences that can (apparently) exist between the acceptance of facilities when considered at a general (i.e., socio-political) versus a local (i.e., community) level but has also provided key insight into the myriad explanations that can account for these differences (e.g., van der Horst, 2007; Jones and Eiser, 2010; Bell et al., 2013). This has included efforts to investigate how project acceptance might differ in different countries and cultures (e.g., Toke et al., 2008; Pietzner et al., 2011).

Taken together, it can be concluded on the basis of research conducted to date, that issues of "place" (including social, cultural, and technological characteristics) and "process" (i.e., engagement and decision-making practices) are of central importance when it comes to understanding how proposed projects or facilities are received and responded to at a local level. This is particularly the case within Westernised democracies, where "policy and institutional changes require support from both individuals and communities" (Peterson et al., 2015, p. 1).

Community Acceptance of CO_2 Utilisation Facilities

While there is a rich literature charting community acceptance of a large number of locally unwanted land-uses (LULUs) (e.g., prisons, power plants, and mental hospitals) (Schively, 2007) relatively little (if any) published research has specifically investigated opinions towards the prospect of CO_2 utilisation facilities. This is despite the fact that there are existing examples of commercial CO_2 utilisation facilities currently in operation (e.g., the Carbon Recycling International "Vulcanol" production plant, Grindavik, Iceland; Carbon8 "accelerated carbonation" facility, Brandon, UK).

To the extent that CO_2 utilisation facilities are affiliated with (and are hence sited alongside) existing industrial operations, one could anticipate that the likelihood of prohibitive local opposition forming to earmarked facilities could be very low. Indeed, for communities living adjacent to such sites, who are familiar with and/or reliant on the extant plant for employment, the prospect of additional operations (and opportunities) might be viewed quite positively (e.g., Van Der Pligt et al., 1986; Jones et al., 2015). It is, however, by no means guaranteed that the presence of extant development will mean that further development will be condoned. For example, concerns over fairness and distributive justice (i.e., the distribution of benefits and burdens) or failings in the inclusivity and/or transparency of the decision-making process, might also shape community level acceptance (e.g., Dobson, 1998; Jones et al., 2011; Ottinger, 2013). Moreover, as technologies, product options and their associated markets develop, diversify, and mature; there is an increased likelihood that more (and more diverse) communities will face the prospect of hosting CO_2 utilisation facilities. This will likely bring much less "familiar" populations into direct contact with such facilities.

We argue that the impact that the attitudes and behaviours of prospective host communities can have on the fate of such facilities, necessitates bespoke research into the nature and determinants of community acceptance towards CO_2 utilisation facilities.

The Risks of Drawing Conclusions Based on CCS Research

It would be relatively easy to draw speculative conclusions about likely community responses towards prospective CO_2 utilisation facilities by accessing the rich literature on "local" CCS development (e.g., Oltra et al., 2012; L'Orange Seigo et al., 2014). However, while there is some logic to this enterprise—bearing in mind the similarity in the terms and the fact that CCS and CO_2 utilisation facilities are both industrial plant designed to treat or "sequester" carbon dioxide—there is also good reason to be cautious due to the abovementioned differences in nature, scale, and intended purpose of these technologies (Bruhn et al., 2016). Moreover, where research has provided participants with the opportunity to consider their opinions of CO_2 utilisation in comparison with CCS (e.g., Jones et al., 2015, 2016), there is evidence of a number of fundamental differences in the perceived risks, costs, and benefits, including at the level of individual facilities, of these technology options.

Crucially, the formative research into public perception that has been completed to date (e.g., Jones et al., 2015, 2016) suggests that it is the transportation and storage of carbon dioxide—as opposed to the capture and/or conversion processes *per se*—that appear to be of most concern to those interviewed. This concern would appear to principally stem from the anticipated risk of CO_2 leakage, which is deemed to at the very least undermine the purpose of the technology or at worst to pose a direct risk of death or illness through contamination of drinking water, explosion and/or asphyxiation (e.g., L'Orange Seigo et al., 2014). While this research does reveal that people do see some risks with CO_2 utilisation facilities (e.g., risks from chemicals, explosion, etc.); currently, it appears that such facilities are likely to be viewed as any other form of generic industrial facility. Thus, it would appear that community level objections to CO_2 utilisation facilities are likely to be grounded in concerns over the prospect of local industrial development *per se*, as opposed to any bespoke risks posed by the CO_2 utilisation facility. It appears as though this tempered risk perception stems from both a trust in operators to run the facilities safely, as well as the comparatively benign, confined, and controlled nature of the processes being proposed; perhaps offset further by the prospect of local economic benefits (e.g., new jobs) (Jones et al., 2015).

Is the Current Indifference to CO_2 Utilisation Facilities a Positive Sign?

The relative indifference regarding the prospect of local development indicated in the studies conducted to date should not be taken to mean that it is guaranteed that there will be no opposition to local facilities. As previously outlined, local opinion towards actual development can differ from that registered when facilities are considered in a more general, abstract and/or hypothetical sense (e.g., Jones and Eiser, 2010; Devine-Wright, 2011; Bell et al., 2013). The fact that the research conducted to date has only focused on the opinions of general, unaffected publics is thus a weakness in making specific predictions about the likely acceptance or rejection of specific projects. Moreover, the findings that have been accrued to date are based upon the responses of a relatively ill-informed public (i.e., people with a low awareness and knowledge of the technology). It is possible that as people learn more about benefits and drawbacks of CO_2 utilisation and/or the prospect of local development becomes more real that "unexpected" local objections could arise (e.g., Bell et al., 2005, 2013).

Taken together, the extant research on LULUs indicates that developers and investors should pay close attention to matters of "place" and "process" (Peterson et al., 2015) when seeking to site facilities. CO_2 utilisation facilities are not a special case in this regard. While there are certain "unique" features of such technologies that might particularly resonate with host communities (e.g., specific perceived risks and benefits), the need to be (a) cognisant and responsive to the specific features and demands of a place and its people; and (b) make decisions in a fair, inclusive, and (ideally) participatory way, is now customary advice for finding common ground with potential host communities (e.g., Beierle and Cayford, 2002; Manzo and Perkins, 2006). That said, bespoke research into the community level acceptance of CO_2 utilisation facilities does not yet exist and this should be a priority for future research.

SUGGESTED RESEARCH AGENDA

In the context of CO_2 utilisation, the factors and actors relating to each of the three dimensions of the triangle of social acceptance (i.e., socio-political, market, and community acceptance) raise a number of novel and interesting research questions. While many of these questions have been outlined in the preceding sections; the following research agenda pulls out *some* of the priorities for future research in this field. This is not intended to be an exhaustive list of research questions but rather an outline of a handful of important avenues for initial inquiry, which are based upon the themes identified within this review article.

Socio-Political Acceptance

Socio-political support among the general public and other stakeholders can fundamentally shape the successful introduction of products and/or deployment of CO_2 utilisation facilities. As such, key CO_2 utilisation stakeholders should be identified as targets for future research (e.g., industry decision-makers, national, and international policy-makers, publics, and the media), and systematic programmes of investigation should be conducted in order to gain deeper insight into the antecedents and consequences of acceptance at this level. This research should seek to recognise and chart regional differences in socio-political acceptance of CO_2 utilisation.

Recommended studies relating to socio-political acceptance include

- A systematic, issue- and organisation-focussed stakeholder analysis in order to identify and clarify the range of stakeholders with connections to the development and deployment of CO_2 utilisation technologies and products (in different regions), as well as the reasons for their interest and/or investment in CO_2 utilisation at the socio-political level.
- A broader and more-detailed analysis of the international media coverage of CO_2 utilisation in order to assess emerging perceptions of CO_2 utilisation technologies (among the media and reported stakeholders) and how these are influencing the public agenda on CO_2 utilisation.
- A systematic analysis of the broader political agenda regarding CO_2 utilisation and how it might influence the investment in and the further research and development of technologies and products. This research should model different investment and development pathways in different policy and legislative scenarios.

Market Acceptance

A number of stakeholders will affect the market acceptance of CO_2 utilisation technologies and products. Notably, these include market actors, whose decisions to invest in CO_2 utilisation technologies and/or to produce, purchase, utilise, or retail CO_2-derived products will significantly shape innovation within the sector. Also, as more CO_2-derived products become available on global markets, the opinions, and choices of consumers will necessarily have an influence of growing importance.

Future research in the area of market acceptance should include

- Detailed identification of market-stakeholders and analysis of their perceptions of CO_2-derived products (including end-consumers) as they become commercially available. This research should seek to compare and contrast preferences for different CO_2-utilisation options and analyse how the preferences are formed, spread and how they affect choice among different consumer-groups.
- A more-detailed and systematic analysis of the acceptance and diffusion of different CO_2 utilisation technologies and products among investors. Studies should specifically investigate how the socio-economic environment and extant path dependencies affect behaviour among different investors.
- Research into intra-firm perception, attitudes, acceptance, and diffusion of CO_2 utilisation technologies and products. In particular, the role that "change agents" have in influencing intra-firm decision making is a relevant area for research.

Community Acceptance

Whether or not specific CO_2 utilisation facilities are welcomed at a local level could have implications for the overall success of the concept. While inferences can be drawn from analogous technological innovation, we currently know little about the community-level acceptance of CO_2 utilisation facilities and less about how opinions might evolve following construction and (successful or interrupted) operation. While some CO_2 utilisation facilities do currently exist, it is only a matter of time before more (and more diverse) communities will be invited to host facilities, either in isolation or in association with other industrial developments (e.g., CCS projects).

Two key questions that should form the basis of systematic future research in this area are:

- To what extent is the relative agnosticism (or indifference) currently shown towards hypothetical CO_2 utilisation facilities mirrored within communities actually hosting facilities and/or facing actual development (i.e., to what extent is there a "social gap" in CO_2 utilisation facility siting, see Bell et al., 2005, 2013)?
- Which of the many "place" and "process" factors identified as influencing local project acceptance (Peterson et al., 2015) are most important in shaping people's attitudes (and behavioural responses) to CO_2 utilisation facility development? For example, how does the presence and reliance on extant industrial development in a community affect acceptance of CO_2 utilisation facilities?

In addition to shedding light on the extant nature of more specific, "local" opinion towards CO_2-utilisation facility development, the findings of such research hold the potential to help inform public communication and engagement activities for use in relation to subsequent projects. Importantly, though, one needs to think carefully about the methods used in this research in order to ensure that a representative sample of community stakeholders are questioned and that informed opinions are assessed (e.g., de Best-Waldhober et al., 2009).

Interactions between the Dimensions of Social Acceptance

Finally, while specific consideration of interactions between the socio-political, market, and community dimensions was beyond the scope of this initial review, it is evidently the case that these three forms of acceptance are often interrelated (Wüstenhagen et al., 2007; Sovacool and Ratan, 2012). As such, a focus of future research should be to develop a better and more comprehensive understanding the nature of these interactions (and implications of thereof) within the context of CO_2 utilisation. For example, one could reflect on how the opinions registered by local stakeholders at the community level (e.g., local authorities, affected publics) might serve to affect more general socio-political level acceptance (e.g., national government) decision making (or vice versa). Similarly, one might investigate how general socio-political acceptance might translate into consumer uptake or rejection of specific CO_2-derived products.

CONCLUSION

Research into the social acceptance of the CO_2 utilisation is currently at an embryonic stage (the first article was published in 2014); however, perceptions of CO_2 utilisation among diverse social stakeholders (e.g., investors, policy-makers, the public) will fundamentally shape the path of CO_2 utilisation technologies and CO_2-derived projects. The aim of the current article was to outline the importance of considering the "social acceptance" of CO_2 utilisation technologies and products, while simultaneously identifying some of the key factors and actors likely to shape this acceptance. We utilised the "triangle of social acceptance" (Wüstenhagen et al., 2007) as a framework for structuring the article in order to help "carve up" this complex and multi-faceted concept into more digestible pieces. Crucially, this review was not designed to be an exhaustive precis and synthesis of *all* of the specific stakeholders and issues that should be considered in this arena, but was rather designed to elucidate the most important players and considerations that should be kept in mind when seeking to broach the subject of social acceptance in the context of CO_2 utilisation.

It is intended that this review and research agenda should form the basis for increased collaborative research between social scientists, pure scientists and engineers around CO_2 utilisation technologies and products; such that development and deployment decisions appropriately recognise and respond to the social context for their introduction (e.g., Jones and Jones, 2016).

AUTHOR CONTRIBUTIONS

All named authors have contributed to all aspects of the writing process, including the initial conception of the review and the drafting and revision of the article. All authors approved the final the version of the article and agreed to be accountable for what it contains.

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Short communication

What a waste! Assessing public perceptions of Carbon Dioxide Utilisation technology

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ABSTRACT

Carbon Dioxide Utilisation (CDU) technologies hold promise by helping to limit atmospheric releases of CO_2 while simultaneously generating saleable products; however, to date there has been very little systematic research into public perceptions of the technology.

This short communication reports briefly upon the results of a small pilot study designed to (a) test a methodology for investigating public perceptions of CDU; and (b) elucidate new understanding of people's attitudes towards the technology.

The results indicate that while people believe that CDU will have economic benefits (e.g., creating employment opportunities and saleable products) there is scepticism over the perceived long term environmental benefits of the technology (e.g., in mitigating climate change).

The findings of this research have important implications for the framing of communications about CDU technology within the public sphere.

1. Introduction

Carbon Dioxide Utilisation (CDU) technologies hold promise by helping to limit atmospheric releases of CO_2 while simultaneously generating saleable products [1]. However, while there is growing investment in the research and development required to test the technical and economic viability of CDU [e.g., 2,3], to date there has been very little systematic research into public perceptions of the technology.

The importance of gauging public opinion should not be underestimated. Numerous analogues exist to illustrate where a failure to properly assess the acceptability of new technologies and then appropriately engage with the general public and/or anticipated 'host' communities, can negatively affect the ease, speed or chance of real world, commercial scale deployment. Examples include GM food [4], and renewable energy [5]. Recently, these public failures have prompted shifts towards more participatory and 'upstream' forms of public engagement around the introduction of new technologies, for example in nanotechnology [6], which seek to engage the public at a much earlier stage [7,8]. With this in mind we firmly believe that research and development of CDU would benefit from systematic research into public perceptions and acceptance of the technology.

2. The current research

In view of the present lack of research into public opinion of CDU, as part of the new UK Centre for Carbon Dioxide Utilisation (CDUUK) and through the CO_2Chem network (http://co2chem.co.uk/) we are conducting a series of studies aimed at learning more about the perceived benefits, risks, utility and relevance of CDU among members of the UK public. This communication will report briefly upon the results of a small pilot study, conducted on 16 participants (10 male, 6 female; 19 54 years) recruited from a University of Sheffield volunteers list, designed to: (a) design and test a *methodology* for investigating public perceptions of CDU; and (b) elucidate *new understanding* of people's attitudes towards the technology. We hope that, as with ongoing research into CCS communication [9 12], the understanding yielded by our research can be used to aid the development of better means of engaging and communicating with members of the general *publics* about CDU.[1]

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[1] The term *publics* is used deliberately so as to recognise the inherent diversity that exists within society; diversity that might co-determine interest, understanding, involvement and opinion of technological innovation, including Carbon Capture Storage and Use technologies.

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3. Method

As a new, unfamiliar family of technologies, CDU presents a challenging context for attitude research. Cognate research into CCS has indicated, for example, that unfamiliarity and low levels of awareness can leave people prone to registering 'pseudo opinions' [13,14]; 'uninformed' opinions that are problematic as they can be weak, changeable, and non directive of people's later thoughts and behaviour. As such, these opinions are not ideal for making policy, investment or facility siting decisions.

In our current programme of studies we are using a mixed methods approach, which combines qualitative focus groups and a follow up information choice questionnaire (ICQ) to assess opinion as described below. Both these techniques have been utilised successfully in studies assessing public opinion of cognate technologies, such as CCS, and offer good forums for the provision and deliberation of information about unfamiliar and/or contentious topics and thus have been associated with the registering more 'informed' opinions [11,14].

For general guidance on the application of social science methods to real world research settings, see, for example, Robson [15] and Bickman and Rog [16].

3.1. Focus groups

The aim of the focus group element of the research was to inform participants about CDU and to promote general discussion of the technology. After completing a short questionnaire designed to record basic demographics and initial awareness about CDU, participants received a short verbal introduction to the technology and watched a short video illustrating the purpose and process of CDU.[2] Using the video a stimulus, participants were then guided through a discussion of CDU technology for approximately 45 60 min and were invited to comment on their general perceptions of the technology, perceived risks and benefits, and the utility of CDU in tackling climate change relative to other options.

3.2. Information choice questionnaire (ICQ)

All participants then completed an ICQ within which they were invited to compare CCS and five CDU process/product options: cement production, plastics manufacture, transport fuel production, methanol production and enhanced oil recovery based on seven criteria: (1) investment payback time; (2) market potential for the products; (3) carbon reduction or abatement potential; (4) safety; (5) cost benefit to the consumer; (6) date to commercial viability; (7) ability to promote 'business as usual' operations. Table 1 summarises the details of the assessment criteria. Information about each option was provided in a comparative 'top trumps' style format.[3] Brief annotations and an illustrative pictorial image were provided alongside a 0 10 expert rating for each criterion.[4] A depiction of our 'methanol production' CDU 'top trumps' card can be seen in Fig. 1 (see Electronic Supplementary Information for full criterion definitions and averaged expert ratings of the technology options).

Having read about the CDU/CCS technologies, participants were asked to: (1) rank the options in order of preference (most to least preferred); (2) rate the extent to which they based their decisions on each assessment criterion; (3) rate how good or bad each option was in the context of reducing CO_2 emissions from industry; and (4) rate the quality of the provided information for bias, trustworthiness, credibility, sufficiency and understandability.

Table 1
Description of the 'top trumps' assessment criteria used to compare different CDU options.

Criteria	Description
Investment payback time	How long it will take the money invested in the storage process or the new technology to be paid back. *The lower the rating, the longer it will take and so the less economically efficient it is.*
Market potential	Whether the product produced by the captured CO_2 will have the potential to sell. *The higher the rating the more potential it has.*
Carbon reduction	Refers to how much carbon is actually being taken out the atmosphere or used to produce another product. *The higher the rating, the more carbon that is removed and therefore the more effective it is.*
Cost benefit to consumer	Refers to whether the price of capturing the CO_2 or transforming it into another product will cost the customer through increased energy prices or whether the profits from the end product will offset this cost. *A higher rating means that the technology is less likely to make energy prices increase.*
Business as usual	Refers to the extent to which the option will enable/disrupt the current ways in which business and society operate; how much 'business' will remain as usual. For example, are we still able to live our day lives and use transport to the same extent. *A higher rating suggests business as usual is more achievable.*
Commercial availability[a]	Measures, in years, how long it will be before this technology is on the market (i.e., available for commercial use). *The greater the number of years the lower the commercial availability.*

[a] 'Commercial availability' was the only criterion where a higher value equated to a less favourable evaluation.

4. Results

The results below detail the headline findings from our pilot research activity. These findings should be considered a prelude to ongoing and more comprehensive work in this area.

4.1. Focus group

Pre participation awareness of CDU was low with only one respondent registering that they had heard of CDU. All participants indicated that they did not know a lot about the technology. Nine participants had no opinion of CDU, three said they were neutral and four said they were fairly or very positive to the technology.

Content analysis of the written notes and audio recordings from the focus groups has identified a number of key themes/issues raised by participants, which apparently have implications for how CDU is presented and communicated.

(1) *Delaying the inevitable*: People believe that CDU may only delay the inevitable release of CO_2 to the atmosphere at high cost, both in terms of financial and energy related costs. There is a feeling that the considerable energy used for CDU could be put to better, and more direct, use elsewhere, for example in providing homes with electricity. This concern is augmented by the belief that the potential carbon savings actualised by investment in CDU will be small, leading people to question the perceived utility, impact and worth of the technology,

[2] The video and other key materials associated with the research (e.g., 'top trumps' comparison cards) are publically available at: www.co2chem.co.uk/research-clusters/public-perception.

[3] 'Top trumps' is a card game where you compare things (e.g., cars or superheroes) on selected criteria (e.g., speed or strength). The higher the score for each criterion the better the thing is. The CDU 'top trumps' were developed in accordance with this concept.

[4] The information and ratings used to create the 'top trumps' cards were produced and validated by 10 academic experts working in the field of CDU, contacted via the CO_2 Chem Network.

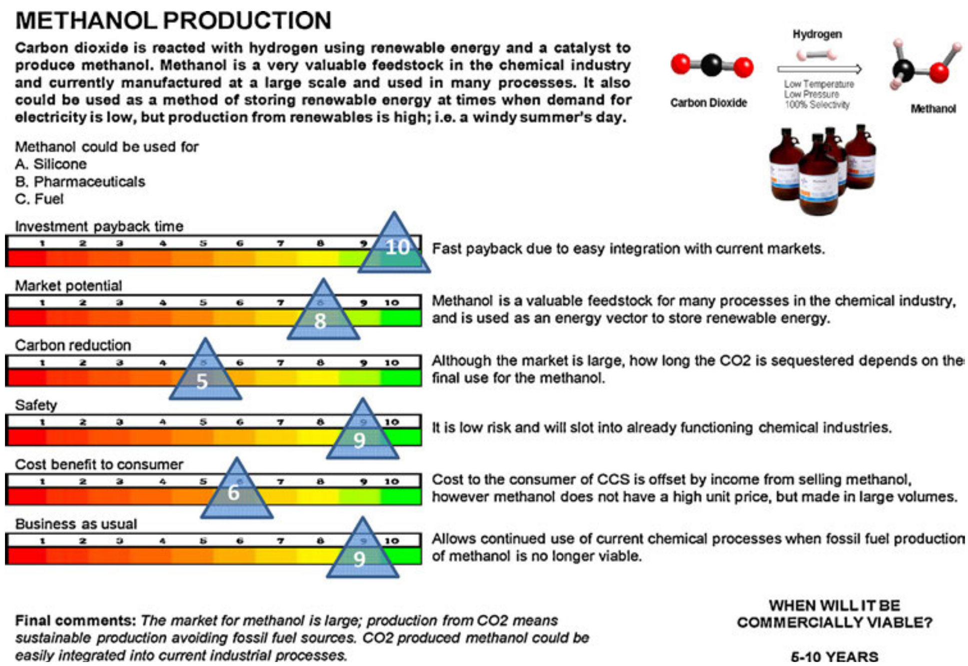

Fig. 1. Example CDU 'top trump' card. Card illustrates methanol production option and provides expert ratings (and justifications) for the option on key evaluative criteria.

particularly as a means of tackling climate change. Indeed, while people do appear to generally value the principle of CDU as an attempt to mitigate climate change, and believe that CDU could help 'buy time' in the fight against climate change, this strength is caveated by the energy intensive nature of the processes, the suggestion that CDU presents only a short term solution to the issue of climate change, concern that CDU does not present the 'right solution' for tackling climate change and could draw funding from other technology and uncertainty about the long term effects of the technology.

(2) *Preventing societal change*: By making use of CO_2 people feel that CDU could be used by the public as an excuse to continue with their current wasteful lifestyles, thereby delaying or undermining efforts to promote action on climate change. CDU is to some extent seen to conflict with carbon reduction policies and as something that will only really address the symptoms of climate change as opposed to its root causes (i.e., wasteful lifestyles). With this in mind, it is reasoned that investment should target behaviour change campaigns to reduce energy use rather than technological fixes, like CDU.

(3) *Employment and economic prospects*: Investment in CDU is anticipated to create new employment opportunities and produce useful, saleable products. Indeed, the employment prospects are seen to be a major strength of the technology, with people tending to see greater economic benefits than environmental benefits from the technology.

Table 2
Comparative preferences for CDU options and mean evaluation of each option as a means of tackling CO_2 emissions from industry.

	Sum of ranks[a]	Mean evaluation (SD)[b]
Methanol production	32	3.31 (0.95)
Cement production	35	3.60 (0.91)
Plastics manufacture	45	3.00 (1.07)
Fuel production	54	2.73 (1.33)
Enhanced oil recovery (EOR)	68	2.31 (1.02)
CCS without CDU	81	3.44 (1.21)

[a] Lower sum score means option was more preferred.
[b] Responses made on 5-point scale (1 = very bad to 5 = very good).

4.2. Information choice questionnaire (ICQ)

Participants tended to agree that the information provided within the ICQ was moderately largely unbiased, trustworthy, credible, sufficient and understandable. While participants noted that they had considered all the information provided to moderate large extent, they relied mostly on the 'carbon reduction potential' information and least on the 'business as usual' information when making their decisions.

Methanol production was the most preferred technology option, closely followed by cement production, and then plastics manufacture, fuel production, EOR and CCS as shown in Table 2. These rankings were roughly comparable to the overall evaluations provided to the options in terms of tackling CO_2 emissions from industry; however, in this context cement production was the most preferred option and CCS was preferred to plastics, fuel manufacture and EOR.

5. Discussion

5.1. New understanding

The results of this preliminary research suggest that while the concept of CDU is not rejected by people, it is greeted with caution. This caution would appear to stem from scepticism over the long term impact of the technology in tackling climate change and a concern that investment in CDU might prevent necessary societal change.

These concerns are reflected in participants' general preferences for the different CDU options and also are perhaps evident in the differences in their self reported reliance on the different assessment criteria when making their decisions, 'carbon reduction potential' > 'business as usual'. In relation to the long term impact on climate change it is noteworthy that the only CDU option to be more favourably evaluated than CCS was cement production. Arguably this is because participants saw cement production as a process that would both make use of CO_2 and fix the carbon indefinitely. That is, the other options were likely to be seen as only delaying (and in the case of EOR increasing) an inevitable release of CO_2 to the atmosphere. Similarly, in terms of preventing societal change, our results indicate that people are apparently least favourable to those options more obviously related to facilitating current wasteful lifestyles, such as a reliance on oil through EOR, plastics and carbon based transportation.

Our participants did, however, see some value to CDU in terms of creating useful products and job opportunities and, to some extent, did value the technology to the extent it was seen as symbolic of attempts to address climate change, although few believed that it was the 'answer' to climate change.

5.2. The methodological point

Initial awareness of CDU was very low among our participants. Only one participant registering that they had heard of CDU and all participants registered that they did not know a lot about CDU. Despite this, however, four participants still registered having a positive or very positive opinion of the technology, not including the person who had registered awareness of the technology. This is indicative of these participants having initially registered pseudo opinions. We argue that this finding validates our decision to employ more discursive and structured methods of attitude assessment within this research, rather than using a basic questionnaire based survey.

As revealed by research into CCS, while it should not be assumed that such methods will produce more favourable attitudes per se, they should serve to improve knowledge of the technology and enhance attitude certainty [e.g., 17]. Importantly, this greater attitude certainty should mean that participants' opinions are more stable and thus likely to be more predictive of their future responses to questions or discussion about CDU technologies [see 18].

5.3. Implications

The findings arising from this research have important implications for how communication about CDU technology within the public sphere should be framed. Studies abound to the importance of considering such issues when investigating and assessing attitudes [19]. Our preliminary results indicate that, due to the noted scepticism of CDU as a means of combating climate change, promotion of CDU on these grounds might not foster the support and acceptance of the technology that one might anticipate. Rather, by emphasising the benefits of the technology in terms of generating useful products and new employment opportunities might hold more value in this respect.

6. Conclusions

This short communication was designed with three key intentions: (1) to *raise awareness* of the importance of considering public perceptions of this emerging family of technologies; (2) to reveal some *new understanding* on this issue that we are generating through our ongoing research at CDUUK; and (3) to outline an innovative mixed methods *approach* to assessing people's in formed opinions of the technology.

Evidently the size and the university based nature of the current sample potentially limit the transferability of these preliminary findings.[5] We are currently expanding upon the present research design to investigate the opinions of a greater number and diversity of individuals to establish if the themes and preferences arising from this research are more common among the general population and within particular stakeholder groups, such as those living in communities likely to host future CDU developments. We would encourage others to do the same.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jcou.2014.05.001.

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[5] The aim of *qualitative* research is not to generate generalisable findings (i.e. where the results of a sample population can be automatically applied to the target population at large) as such, but rather to elucidate specific areas of interest to a researcher. Q*ualitative* studies tend to instead generate 'transferable' findings; i.e., findings which can be actively applied and tested by others in contexts beyond the immediate location of the study where similar people, situations or phenomena exist [see 16].

Appendix for Chapter 8

CarbonNext
The Next Generation of Carbon for the Process Industry

CarbonNext Survey

Information

CarbonNext is a Horizon2020 project funded by the European Commission to investigate the opportunities for alternative carbon feedstocks as we move away from using fossil fuels as the main source. We need to find new sources of carbon for industrial process if we are to create a sustainable chemical process industry in Europe that reduces its carbon dioxide emissions.

CarbonNext's objective is to evaluate the potential of new carbon sources in Europe. It will primarily focus on new sources of carbon to be used as a feedstock and secondarily the impact this will have on on energy availability, price and emissions. The evaluation will include multiple alternative carbon sources: carbon dioxide, carbon monoxide and other non-conventional fossil sources such as shale gas, tar sands and coal bed methane. CarbonNext will map and evaluate these alternative carbon sources and investigate symbiotic value chains between industrial sectors - where can the emission of one industry become the feedstock of another? Questions will be answered such as; where is the carbon? How much is there and is it clean enough to use? Would the price be affordable and what kinds of technologies are needed to bring it in the value chain? Are the sources connected to established infrastructures? And last but not least, how will the current political framework conditions influence the result of the evaluation?

This Survey focuses on the factors that are inhibiting SMEs (<250 employees) and larger companies from implementing technologies that use alternative carbon sources such as CO2 or CO.
This survey is conducted in accordance with the Ethics Policy of the University of Sheffield. All the information that is collected during the course of the research will be kept strictly confidential. You will not be able to be identified in any reports or publications. By completing this survey you are giving consent to take part in this research for CarbonNext. You may at anytime leave the survey and your data will be discarded.

* 1. In which country is your organisation based?

* 2. In which country/countries does your organisation operate?

* 3. How many employees does your organisation have?

- ○ 1-5
- ○ 6-10
- ○ 11-20
- ○ 21-50
- ○ 51-100
- ○ 101-250
- ○ 250+

* 4. What sector is your organisation part of?

- [ ] Chemicals
- [ ] Minerals/Construction
- [ ] Fuels
- [ ] Metals
- [ ] Bio-based
- [ ] Waste
- [ ] Energy
- [ ] Other

Please specify the exact field

5. What stage is your organisation at? (you can have more than one answer for different areas of the organisation).

- [ ] Research (TRL 1-3)
- [ ] Pilot (TRL 4-6)
- [ ] Demonstrator (TRL 6-8)
- [ ] Commercial (TRL 9)
- [ ] Other (please specify)

6. Please indicate if any of the below listed points apply for your organisation? Please select all that apply.

- [ ] Member of Spire
- [ ] Member of Cefic
- [ ] Member of Eurofer and/or Eurometaux
- [ ] Member of The European Cement Association
- [ ] Member of Hydrogen Europe and/or European Hydrogen and Fuel Cell Association
- [ ] Member of CO2Chem or CO2 Value Europe
- [ ] Have participated in the German funding programme on CO2 utilisation
- [ ] Member of KIC's (e.g. Climate, Energy, Raw materials)
- [ ] Member of BBIC (Bio-based Industries consortium)
- [ ] Other CO/CO2 or low carbon related organisations (please specify)

7. Does your organisation have goals for reducing environmental impacts?

- ○ Yes
- ○ No
- ○ Unsure

8. If yes, what areas do the environmental goals impact?

- [ ] Use of renewable energy
- [ ] Energy efficiency
- [ ] Waste reduction
- [ ] Resource efficiency
- [ ] Pollution abatement
- [ ] Recycling
- [ ] Carbon footprint
- [ ] Other (please specify)

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CarbonNext Survey

* 9. Is your organization interested in options that could allow waste CO_2 or CO to be used to create a value added product?

- ◯ Yes
- ◯ Yes, in theory but haven't explored further
- ◯ No
- ◯ Unsure

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CarbonNext Survey

Alternative carbon technologies

10. Is your organisation an emitter of CO/CO2 who would like to find utilisation options or do you use CO/CO2 as a raw material?

- ◯ Emitter of CO/CO2
- ◯ User of CO/CO2
- ◯ Both
- ◯ Unsure
- ◯ Other (please specify)

* 11. On a scale from 1 (never heard of) to 5 (extremely familiar), please rate how familiar you are with carbon dioxide utilisation

1-Never heard of	2 - vague	3 - basic	4 - good	5 - Very familiar
◯	◯	◯	◯	◯

* 12. On a scale from 1 (never heard of) to 5 (extremely familiar), please rate how familiar you are with these specific CO2 utilization technologies. Please answer for each option.

	1-Never heard of	2 - vague	3 - basic	4 - good	5 - Very familiar
Polymer production from CO2/CO	○	○	○	○	○
Bulk Chemical production from CO2/CO	○	○	○	○	○
Fine Chemical production from CO2/CO	○	○	○	○	○
Fuel production from CO2/CO	○	○	○	○	○
Mineral production from CO2/CO	○	○	○	○	○
CO2/CO bio-based technologies	○	○	○	○	○

* 13. Assess the importance of the following factors influencing your interest in alternative carbon technologies? Please answer for each option

	Very important	Important	Moderately important	Low importance	Not important	Not applicable
Regulation/taxation	○	○	○	○	○	○
New business opportunities/diversification	○	○	○	○	○	○
Broaden your raw material base	○	○	○	○	○	○
Using current waste streams	○	○	○	○	○	○
Public relations/social responsibility	○	○	○	○	○	○
Reducing carbon footprint	○	○	○	○	○	○
Making 'greener' products	○	○	○	○	○	○
Security of supply of raw materials	○	○	○	○	○	○
Use of excess energy/heat	○	○	○	○	○	○

* 14. To what extent do the following factors prevent your organisation from implementing technologies to use alternative sources of carbon to their full potential?

	Very high extent	High extent	Moderate extent	Low extent	Not at all
Lack of technical knowledge	○	○	○	○	○
Unsure of legal frameworks	○	○	○	○	○
Regulatory barriers	○	○	○	○	○
Lack of knowledge of market opportunities	○	○	○	○	○
Lack of knowledge of economics of the process	○	○	○	○	○
Economic feasibility (poor business case)	○	○	○	○	○
Lack of government subsidies	○	○	○	○	○
Lack of private investors	○	○	○	○	○
Lack of public funding/support	○	○	○	○	○
Lack of partners	○	○	○	○	○
Lack of infrastructure (pipelines, capture facilities etc)	○	○	○	○	○
CO/CO2 price	○	○	○	○	○

15. Please provide further details on the barriers you encounter and how these could be overcome

16. If technical knowledge is a factor, please assess in which areas you are lacking information

- [ ] Knowledge of underpinning science
- [ ] Knowledge of technologies that could be applicable to your organisation
- [ ] Knowledge of impacts on your energy supply
- [ ] Knowledge of impacts on your wastes and emissions
- [ ] Knowledge of scale-up
- [ ] Knowledge of how local infrastructure and/or how symbiotic opportunities could be utilised
- [ ] Knowledge of life cycle analysis for your specific situation
- [ ] Knowledge of techno-economic analysis for your specific situation
- [ ] Other - please detail below

Please give further details

* 17. What impact do the following regulations/policies have on your decision to implement alternative carbon feedstocks?

	Negative impact	No impact	Positive impact	Unknown
Emissions Trading Scheme (ETS)	○	○	○	○
Waste Directive	○	○	○	○
Fuel Quality Directive (FQD)	○	○	○	○
Renewable Energy Directive (RED)	○	○	○	○
Clean Energy Package	○	○	○	○
Inconsistent policies between countries	○	○	○	○
Circular economy package	○	○	○	○

Comments - please give further details on the positive and negative impacts you have encountered.

18. Please tell us about any other factors that are influencing or could influence your organisation's use of alternative carbon technologies?

19. What factors could increase your interest in new sources of carbon? Please tick all that apply.

- [ ] Carbon Tax or increase in ETS price
- [ ] Increase in fossil energy prices
- [ ] Resource scarcity/ need to diversify feedstocks
- [ ] Increase in availability of renewable energy
- [ ] Customer pressure for lower environment impacts
- [ ] More studies on business case
- [ ] Ready availability of CO/CO2
- [ ] Major government push
- [ ] Other (please specify)

20. Thank you for completing the CarbonNext survey. If you have any feedback please contact, katy.armstrong@sheffield.ac.uk, or add it in the box below.