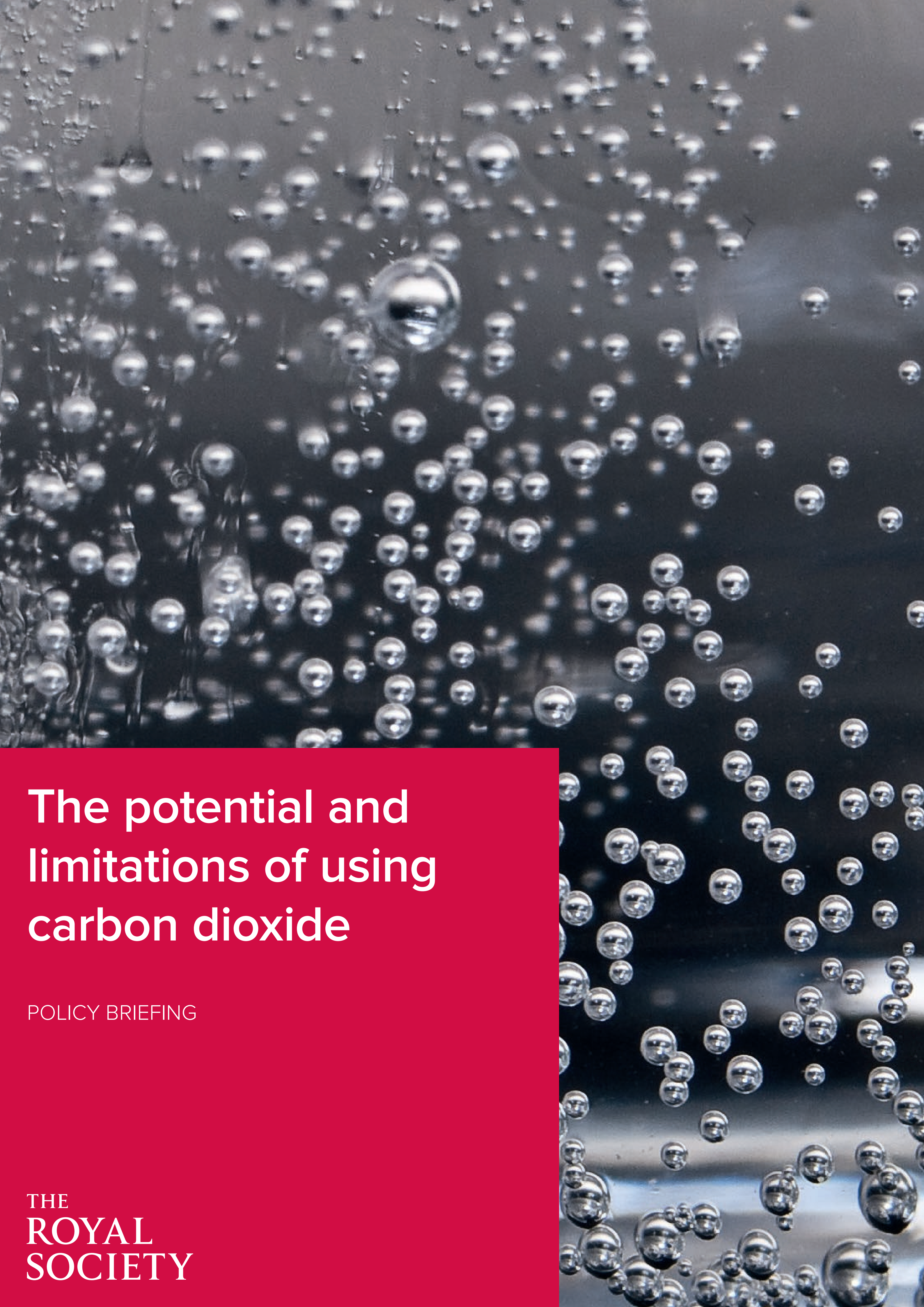

The potential and limitations of using carbon dioxide

POLICY BRIEFING

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POLICY BRIEFING

Politics and science frequently move on vastly different timescales. A policymaker seeking evidence on a new policy will often need the answer in weeks or months, while it takes years to design and undertake the research to rigorously address a new policy question. The value of an extended investigation into a topic cannot be understated, but when this is not possible good evidence is better than none.

The Royal Society's series of policy briefings is a new mechanism aiming to bridge that divide. Drawing on the expertise of Fellows of the Royal Society and the wider scientific community, these policy briefings provide rapid and authoritative syntheses of current evidence. These briefings lay out the current state of knowledge and the questions that remain to be answered around a policy question often defined alongside a partner.

The potential and limitations of using carbon dioxide
Issued: May 2017 DES47801
ISBN: 978-1-78252-267-6

This report can be viewed online at
royalsociety.org/low-carbon-energy-programme

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Executive summary

The UK faces a challenge in deciding how it can transit to a low carbon future whilst pursuing an active industrial strategy that creates growth and jobs in the short and medium term. The economics of large scale carbon capture and storage has raised interest in the potential of using carbon dioxide.

This policy briefing examines the science of using carbon dioxide as a feedstock.

The technology for using carbon dioxide in applications such as synthetic fuels for aviation through to the manufacture of a range of speciality chemicals is available. These new synthetic routes can offer benefits to the final product such as cleaner fuels and polymers, thereby adding greater value. A number of companies are already exploring these areas. It is likely that research currently underway will lead to further optimisation and commercialisation of synthesis routes and new routes to transforming carbon dioxide in greater volume.

There are various estimates as to how much carbon dioxide can be used, depending on the particular use balance. The thermodynamic stability of carbon dioxide means that many transformations require energy input. This energy must be low-carbon for such transformations to make sense, and further they must offer advantages over other deployment of the resources involved. Life cycle analyses of the thermodynamics and economics will be needed to understand the net contribution of specific uses of carbon dioxide.

Given the timescales necessary to invent, scale, commercialise and industrially deploy processes that use carbon dioxide, continuing research is needed to ensure future progress. Key challenges include improving the fundamental understanding of catalysis; the need to produce cheap green hydrogen at scale; and developing sources of competitively priced low carbon energy which can drive carbon dioxide conversion to products. Tackling these challenges will need to be complemented by advances in process and reaction engineering and novel process design. Further, international partnerships are required to ensure breakthroughs. Those partnerships are being developed by the Royal Society.

The commercial potential for specific uses of carbon dioxide must be better understood, as there is an opportunity for the UK to develop leadership in sustainable manufacturing. Demonstrators are required to test technologies at scale and explore integration with existing processes to better understand the techno-economics which will help de-risk further investment. The Port Talbot steel works has made an offer to act in this capacity.

The UK has a strong history of innovation and commercial leadership in both catalysis and materials critical technologies. On the basis of the current evidence this research and development could enable substantial growth in the use of carbon dioxide. Exploiting the widespread availability of carbon dioxide would reduce UK dependence on imported hydrocarbons, increase the UK's security of supply in key chemicals and materials and drive growing commercial opportunities in supply of carbon dioxide based products.

The case for using carbon dioxide

Following commitments made in Paris at the 2015 United Nations Climate Change Conference, the UK faces a challenge in deciding how it can transit to a low carbon future whilst pursuing an active industrial strategy that creates growth and jobs in the short and medium term. Carbon dioxide emissions are at the heart of the decarbonisation challenge. One option to reduce carbon dioxide emissions is to capture and store carbon dioxide. Carbon capture and storage could store 15% of current UK carbon dioxide emissions by 2030 and up to 40% by 2050[1]. However, according to the National Audit Office, concerns were raised about the costs of carbon capture and storage[2]. This has therefore raised interest in the potential of capturing and then adding value to carbon dioxide, rather than storing it geologically.

Carbon dioxide accounted for 81% of total UK greenhouse gas emissions in 2015[3]. It is emitted from a variety of diffuse and point sources (see Table 1), and can be captured and processed more readily when emitted from point sources.

TABLE 1

UK carbon dioxide emissions by sector in 2015[4]

Emissions from	Mt
Fuel combustion for electricity generation and other energy production sources.	136.4
Domestic aviation, road transport, railways, shipping, fishing and aircraft support vehicles.	118.8
Combustion in commercial sectors, such as refrigeration and air conditioning.	68.6
Fuel combustion for heating and cooking, garden machinery, and fluorinated gases released from aerosols and metered dose inhalers.	63.4
Livestock, agricultural soils, stationary combustion sources and off-road machinery.	5.2
Waste disposed of to landfill sites, waste incineration, and the treatment of waste water.	0.3
Industry except for those associated with fuel combustion such as cement, iron and steel production.	12.1

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1. Parliamentary Advisory Group on CCS (Carbon Capture & Storage). 2016 Lowest Cost Decarbonisation for the UK: The Critical Role of CCS. See http://www.ccsassociation.org/news-and-events/reports-and-publications/parliamentary-advisory-group-on-ccs-report/ (accessed 22 February 2017).
2. NAO (National Audit Office). 2016 Sustainability in the Spending Review. See https://www.nao.org.uk/report/sustainability-in-the-spending-review/ (accessed 17 February 2017).
3. BEIS (Department for Business Energy & Industrial Strategy). 2015 Data from: UK Greenhouse Gas Emissions, Final Figures (Statistical Release: National Statistics). See https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-2015 (accessed 21 February 2017).
4. *Op. cit., note 3.*

There are various estimates as to how much carbon dioxide is already used globally, ranging from approximately 116Mt[5] to 222Mt[6] of carbon dioxide per year. There are also various future estimates, ranging from approximately 180Mt[7] to 200Mt[8] of carbon dioxide per year to manufacture polymers and other chemical products; and from approximately 1800Mt[9] to 2000Mt[10] of carbon dioxide per year to manufacture synthetic fuels. These future estimates suggest that approximately 0.5 – 0.6% and 5 – 6% of global carbon dioxide emissions could be used, respectively. However, there is one estimate that suggests approximately 15% of global emissions of carbon dioxide could be used per year by 2030[11]. In terms of net carbon dioxide reduction, technologies using carbon dioxide are likely to account for less than 1% of global emissions reduction[12]. For net emissions reduction, the carbon dioxide used to manufacture products must be recaptured at the end of product lifetimes, and that will affect the cost and energy balance.

While these estimates relate to global carbon dioxide use, the UK government commissioned a study into the potential of industrial carbon dioxide capture for storage or use in the UK. The study considered the UK's existing largest sources of carbon dioxide emissions from industrial sources in the cement, chemicals, iron and steel, and oil refining sectors. It is these point sources, and not the dilute carbon dioxide in the atmosphere, that are the focus of consideration in this briefing. The study estimated that by 2025 approximately 8 – 9Mt ('very high scenario'), 3 – 4Mt ('high scenario') or 0.5 – 0.7Mt ('moderate scenario') carbon dioxide could be used per year[13]. These scenarios are equivalent to approximately 0.1 – 2.2% of net total carbon dioxide emissions in the UK (as shown in Table 1).

These estimates show that the scale of carbon dioxide use is more limited than that which can potentially be stored with carbon capture and storage. Nonetheless, using carbon dioxide to manufacture fuels, chemicals and materials could reduce the need to extract and use fossil fuels, although low carbon sources of energy would be needed to drive the chemical conversion of the carbon dioxide in many cases, because of the thermodynamic stability of carbon dioxide. To provide a sense of scale, over 90% of plastics produced are derived from fossil feedstocks which currently represents approximately 6% of global oil consumption sourced from crude oil that could increase to 20% by 2050[14].

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5. Otto A, Grube T, Schiebahn S, Stolten D. 2015 Closing the loop: captured CO_2 as feedstock in the chemical industry. *Energy. Environ. Sci.* **8**, 3283-3284. (doi:10.1039/c5ee02591e).
6. Naims H. 2016 Economics of carbon dioxide capture and utilization: a supply and demand perspective. *Environ. Sci. Pollut. Res*. **23**, 22226-22241. (doi:10.1007/s11356-016-6810-2).
7. Olfe-Krautlein B, Naims H, Bruhn T, Lafunete A, Tobias M. 2014 IASS Fact Sheet 2/2014: CO_2 as an asset? Potsdam: IASS (Institute for Advanced Sustainability Studies).
8. *Op. cit., note 6.*
9. *Op. cit., note 7.*
10. *Op. cit., note 6.*
11. The Global CO_2 Initiative & CO_2 Sciences. 2016 A Roadmap for the Global Implementation of Carbon Utilization Technologies. See https://www.globalco2initiative.org/documents/CO2U_ICEF_Roadmap_FINAL_2016_12_07.pdf (accessed 23 February 2017).
12. Mac Dowell N et al. 2017 The role of CO_2 capture and utilization in mitigating climate change. *Nat. Clim. Change.* **7**, 243-249. (doi:10.1038/nclimate3231)
13. Element Energy. 2014 Demonstrating CO_2 capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: A techno-economic study. See https://www.gov.uk/government/publications/co2-capture-in-the-uk-cement-chemicals-iron-steel-and-oil-refining-sectors (accessed 26 February 2017).
14. WEF (World Economic Forum). 2016 The New Plastics Economy: Rethinking the future of plastics. See https://www.weforum.org/reports/the-new-plastics-economy-rethinking-the-future-of-plastics (accessed 20 February 2017).

Current and future uses of carbon dioxide

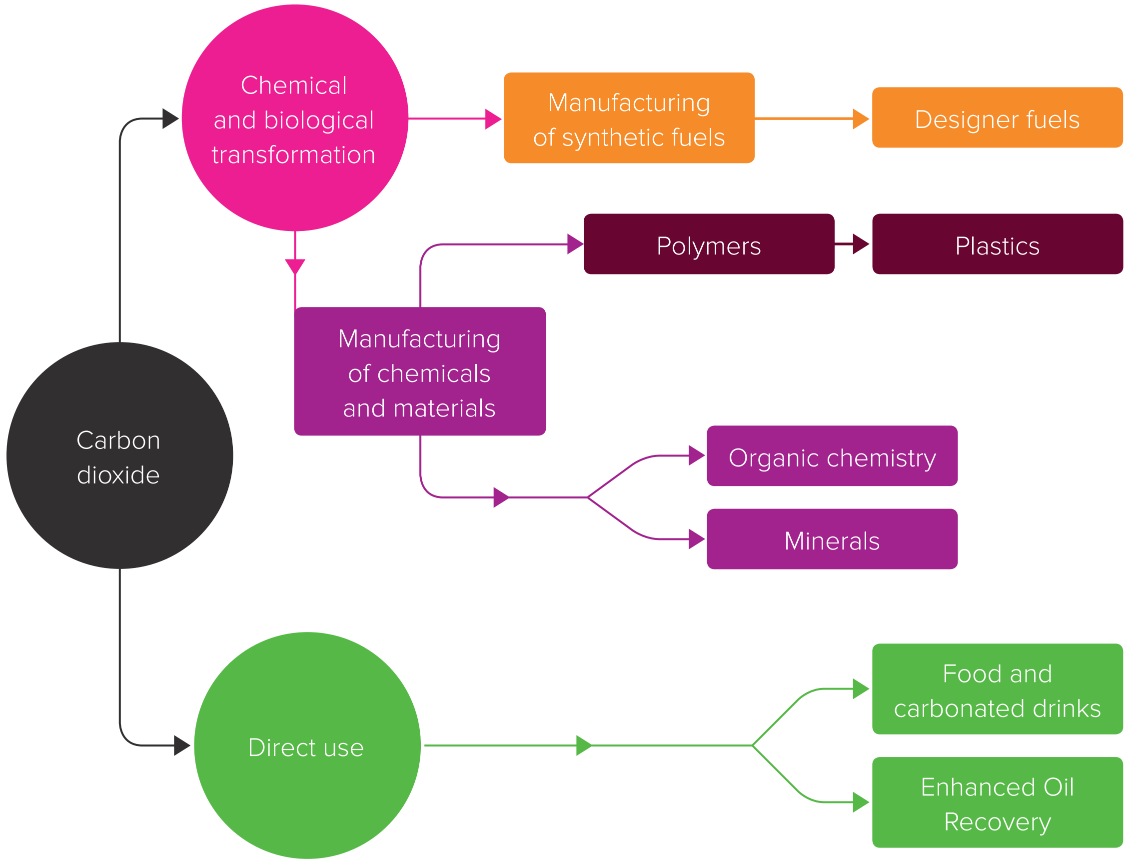
Carbon dioxide has been used in industrial processes for over a hundred years[15]. Those processes include salicylic acid manufacture which dates back to the 19th century; urea which has been chemically synthesized since the 1920s and cyclic carbonates have been manufactured since the 1950s.

Carbon dioxide is often used directly; for example, in enhanced oil recovery, food and carbonated drinks. However, research is exploring new chemical and biological processes to transform carbon dioxide into a feedstock for manufacturing processes on a large scale. (See Figure 1).

> Research is exploring new chemical and biological processes to transform carbon dioxide into a feedstock for manufacturing processes on a large scale.

FIGURE 1

Uses of carbon dioxide



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15. Kleij A, North M, & Urakawa A. 2017 CO_2 Catalysis. *ChemSusChem*. **10**, 1-4. (doi: 10.1002/cssc.201700218).

3.1 Manufacturing synthetic fuels

3.1.1 Current uses

Synthetic fuels are liquid fuels manufactured from coal, natural gas, and biomass feedstocks via chemical conversion processes. These conversion processes can involve either direct conversion into liquid transportation fuels; or indirect conversion whereby the coal, natural gas or biomass is first converted into a mixture of carbon monoxide and hydrogen called synthesis gas ('syngas'). Syngas is produced either by reacting steam and/or oxygen with coal or biomass in a gasification process or by reacting natural gas through a steam methane reformation process. Steam methane reforming of natural gas is also the most common method of commercially producing hydrogen at industrial scale. However, these reactions result in significant carbon dioxide emissions.

Syngas is processed into liquid transport fuels through various conversion processes. The Fischer Tropsch process reacts syngas with a catalyst to manufacture liquid fuels, such as diesel fuel and jet fuel. Syngas can be reacted with catalysts to manufacture methanol to produce liquid fuels. Methanol can be used as a blend with conventional petrol and/or as a fuel in its own right. Methanol is also used to make other fuels, such as dimethyl ether instead of diesel fuel.

3.1.2 Future uses

Manufacturing syngas and methanol directly from carbon dioxide could provide an alternative source of fuels (see Figure 2), increasing the UK's security of supply and reducing its dependence on oil and gas imports. However, new or improved catalysts and processes are required for that to happen. It should be noted that methanol is a cheap commodity and it may be difficult to compete economically with traditional syngas production from fossil sources that is highly optimised and a mature technology. Alternative synthetic fuels that could be made using carbon dioxide and low carbon energy are the subject of current research[16,17].

Synthetic fuels could displace fossil fuels in sectors that are more difficult to decarbonise. For example, new liquid based fuels will be needed in transport sectors, especially aviation[18], marine[19] and road haulage[20]. They can act as both a transition technology in the short and medium term, as well as a long-term opportunity to reduce emissions from transportation as they have the capacity to be combusted in a cleaner manner.

3.1.3 Biomass and biofuels

Plants convert carbon dioxide and water into biomass when they capture sunlight to drive the process of photosynthesis.

The International Renewable Energy Agency estimates that approximately 40% of global biomass supply in 2030 would originate from agricultural residues and wastes with 60% being supplied from energy crops and forest products including forest residues. However, the inefficiency of photosynthesis to convert solar energy to biomass and the uncertainties surrounding the production of energy crops make this less attractive[21].

In the future, sustainable biomass may be in short supply compared to the growing world demand for fuels and chemicals. This would make carbon dioxide a more attractive source for fuel and chemical manufacture, subject to the thermodynamic constraints noted above.

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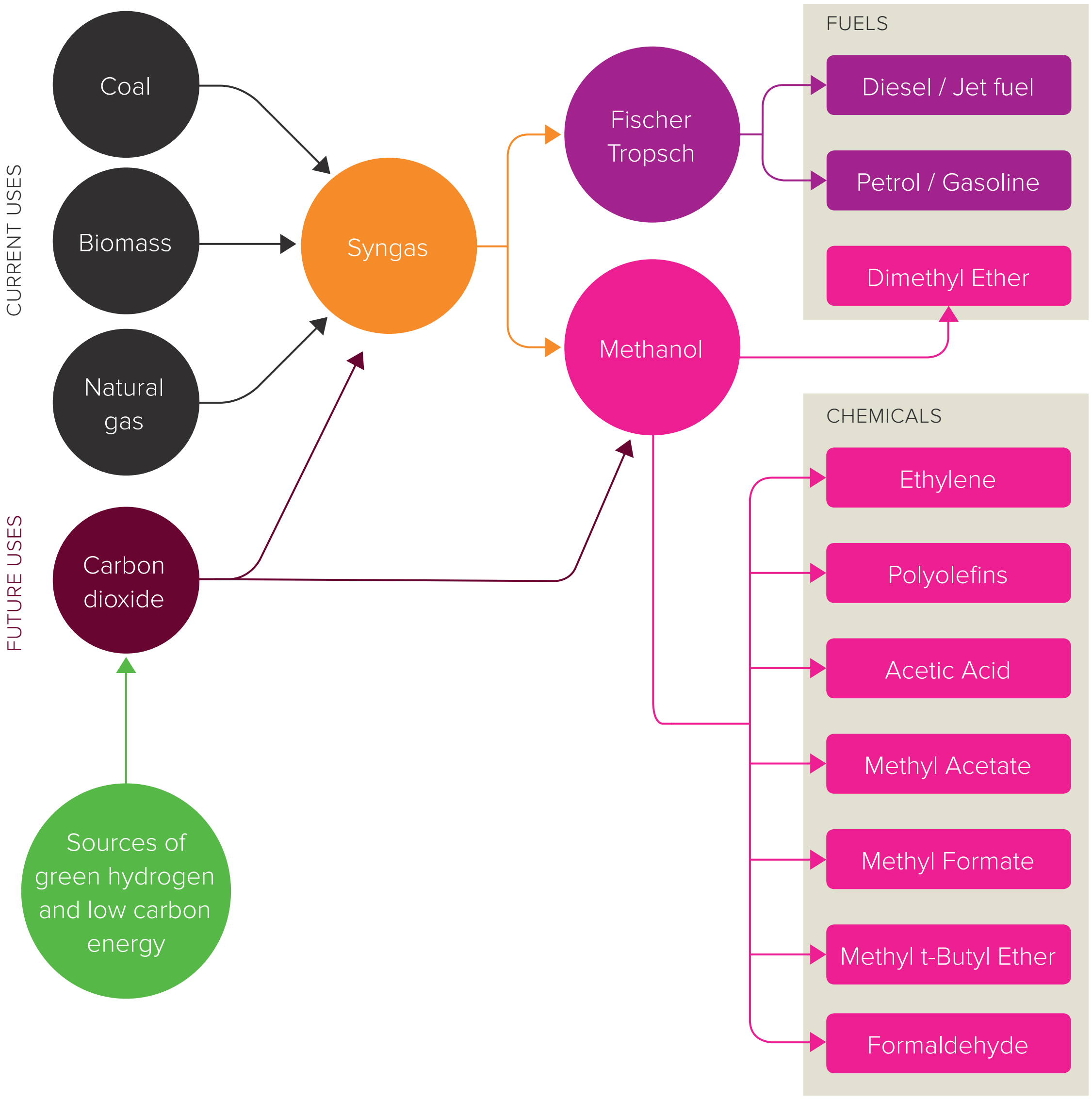
16. Grinberg Dana *et al*. 2016 Nitrogen-Based Fuels: A Power-to-Fuel-to-Power Analysis. *Angew. Chem. Int. Ed. Engl*. **55**, 8798-8805. (doi:10.1002/anie.201510618).
17. Sternberg A & Bardow A. 2015 Power-to-what? – Environmental assessment of energy storage systems. *Energy. Environ. Sci*. **8**, 389-400. (doi:10.1039/C4EE03051F).
18. Virgin. Low carbon fuel breakthrough for Virgin Atlantic. See https://www.virgin.com/richard-branson/low-carbon-fuel-breakthrough-virgin-atlantic, (accessed 21 February 2017).
19. Stena Line. Stena Germanica's Methanol Conversion. See http://www.stenalinefreight.com/news/Methanol-project, (accessed 17 February 2017).
20. Volvo. Mack Trucks tests alternative fuel DME. See http://www.volvogroup.com/en-en/news/2017/jan/mack-trucks-tests-alternative-fuel-dme.html (accessed 24 January 2017).
21. Cotton A *et al*. 2015 Photosynthetic constraints on fuel from microbes. *Front. Bioeng. Biotechnol.* **3**, 1-5. (doi:10.3389/fbioe.2015.00036).

FIGURE 2

Converting carbon dioxide into methanol – current and future use



TEXTBOX 1

Mineralising carbon dioxide to make new construction products

Carbon8 Systems was set up in 2006 as a spin-out company from the University of Greenwich. In 2010, Carbon8 Systems licenced their technology for the treatment of air pollution control residues from waste to energy plants in the UK to Carbon8 Aggregates. Carbon8 Aggregates owns and operates two plants in the UK and plans to expand to at least five plants in the next few years. These plants are located near local waste plants and customers to reduce transport costs. The University of Greenwich has provided indirect support to Carbon8 Systems through access to its laboratories, including high quality analytical facilities and time for research staff. Carbon8 Systems has received three rounds of UK government funding. Some of the fundamental development work on the use of the technology to treat air pollution control residues was funded by a Knowledge Transfer Partnership between the University of Greenwich, Viridor Waste Management and Carbon8 Systems. In 2009, the company was awarded £60,000 through the Carbon Abatement call of Innovate UK. This helped fund the proof of concept trials, using point source carbon dioxide from a landfill flare, which gave the founding partners the confidence to form Carbon8 Aggregates.

3.2 Manufacturing chemicals and materials

3.2.1 Current uses

Products are now being made in novel ways from carbon dioxide, this includes organic chemicals as well as mineralised products.

Building materials for the construction industry provide an interesting example of mineralisation. In natural carbonation reactions, carbon dioxide reacts with calcium or magnesium minerals, to produce carbonates, the main constituent of limestone. By modifying the reaction conditions using accelerated carbon technology, these reactions can be performed in hours rather than the years taken in nature (see Textbox 1). Many industrial residues generated by thermal processes, such as cement kiln dust, iron and steel slag, coals fly ash and bauxite residue, containing lime or appropriate calcium silicates can readily react with carbon dioxide. In doing so, the contaminants in the residues are stabilised and solidified so that they can be used to manufacture new products.

Carbon dioxide has been used to manufacture polymers, such as polyurethanes and polycarbonates. The polymers may comprise 30 to 50% by mass carbon dioxide in the polymer backbone. Polymer products made from carbon dioxide are being commercialised by various companies (see Textbox 2).

These and other polymers that use carbon dioxide offer a range of performance and functionality suitable for commercial application in multiple industry sectors, especially where sustainability is an important product attribute. Polymers derived from carbon dioxide can be produced and processed using the existing infrastructure for petrochemical based polymer manufacturing[22, 23].

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22. Innovate UK IB-IGT (Industrial Biotechnology Innovation Growth Team). 2015 Journey of industrial biotechnology: the opportunity for growth, Innovate UK. See: https://connect.innovateuk.org/documents/3091671/22707213/Journey%20of%20Industrial%20Biotechnology (accessed 23 February 2017).

23. Zhu Y, Romain C, Williams C. 2016 Sustainable polymers from renewable resources. *Nature.* **540**, 354-362 (doi:10.1038/nature21001)

A key challenge is to develop catalysts allowing carbon dioxide to be used to produce mega-tonne scale products.

TEXTBOX 2

Reusing carbon dioxide to make polymers

Econic Technologies is an SME employing 20 scientists and engineers in Macclesfield and London. It was formed in 2011 from academic research at Imperial College London and has more than 20 patent families. The company sells catalysts that allow carbon dioxide to be converted into polymers used in mattresses, automotives, home insulation and clothing. Their customers are major chemical companies that currently produce these materials from petrochemicals. Their catalysts allow very high inclusion of carbon dioxide; can operate at less than 10 bar pressure, allowing the technology to be retrofitted into existing plants. The company has been supported by the UK government, including by Innovate UK funding (£500,000) and by funding from DECC (£500,000) which allowed the testing of carbon dioxide captured from a UK coal fired power station (Ferrybridge). The testing demonstrated high performance using this raw material- equivalent to using purified carbon dioxide from gas suppliers. Econic Technologies is currently supported by H2020 SME funding (£2M) which supports construction of a demonstrator plant in Macclesfield. Econic Technologies has also raised >£15M investment from private sources.

3.2.2 Future uses

Methanol offers a new route to a range of commodity and platform chemicals including acetic acid, olefins, vinyl acetate, ethyl acetate, ethanol, ethylene glycol and higher alcohols. More effective catalysts for these processes, for example offering higher selectivity to specific olefins, are needed.

Further, the scale of current use of carbon dioxide to manufacture polymers, such as polyurethanes and polycarbonates, could be increased. High value markets, including construction materials (replacing glass, steel and cement in some cases), composites for aerospace; electronic components, battery electrolytes; sensing and diagnostic materials are potential outlets for these materials. New catalysts could not only increase the efficiency of production but also increase the number of new products that could be manufactured.

3.3 Regional approaches to supporting carbon dioxide uses

Existing feedstocks, infrastructure and supply chains could support smaller scale carbon dioxide use industries. Regional approaches may be more attractive[24], and there are already regional opportunities to support carbon dioxide uses in North East England and Wales (see Textbox 3).

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[24] *Op. cit.*, note 6

TEXTBOX 3

Regional opportunities for using carbon dioxide

A review for the Tees Valley Combined Authority explored the potential of carbon dioxide use in the North East[25]. The Tees Valley industrial cluster contains 58% of the UK's chemical industry, worth approximately £2.5 billion Gross Value Added. Industries include steel, ammonia, hydrogen, ethylene, fine chemical and plastics production. The Tees Valley is also responsible for 5.6% of the industrial emissions in the UK. The review considered the maturity of different technologies, and recommended that mineralisation is the most suitable application for near term deployment in the Tees Valley due to its technological maturity and due to waste ashes currently being subject to costly pre-treatments and disposal charges. The review recommended developing a demonstration project for carbon dioxide use in the Tees Valley.

Port Talbot Steelworks produces carbon dioxide, carbon monoxide and hydrogen, and has land suitable for renewables, including the option of an offshore windfarm and multiple sources of high grade waste heat. All of these emissions make the steelworks a potential site to demonstrate and compare different carbon dioxide use technologies. The waste heat, renewable energy and carbon dioxide streams at Port Talbot steelworks and surrounding area are already being modelled as part of a project led by researchers at Cardiff University. If the trials are successful they could then be transferrable to other industries such as the cement industry. Since Port Talbot steelworks emits approximately 8Mt of carbon dioxide per year – approximately 15 to 20% of Wales' carbon dioxide emissions – carbon dioxide reuse could make a significant impact on the carbon footprint of Wales.

Image:
Steel works at Port Talbot

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[25] Armstrong K, Styring P, Wilson G. 2016 Carbon Dioxide Utilisation in the Tees Valley: Possibilities and Potential. Sheffield: UK Centre for Carbon Dioxide Utilization, University of Sheffield.

Major scientific challenges to using carbon dioxide

The challenges facing different uses of carbon dioxide may require a targeted approach to make the best collective use of the UK's world leading expertise.

Fundamental research will be needed to tackle major scientific challenges, including improving fundamental understanding of catalysis coupled with the development of more effective catalysts; the need to produce green hydrogen; and developing sources of low carbon energy to drive the chemistry. The outputs of this research would need to consider the economic and operational realities of industry when deployed.

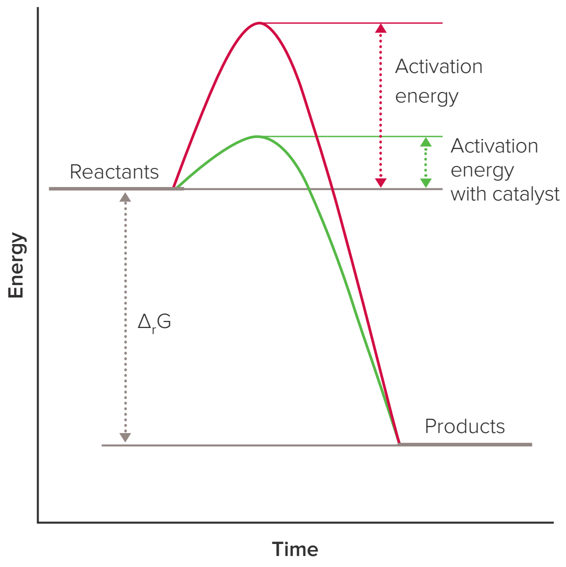
4.1 Improving fundamental understandings of catalysis

Catalysis is the key technology enabling nearly all uses of carbon dioxide (see Figure 3 for an overview of catalysis). Carbon dioxide is stable and so energy and catalysts are needed so that reactions can proceed that would otherwise not take place[26,27]. Improved understanding is needed so that new catalysts can be developed that operate at more favourable conditions, such as lower temperatures and under lower pressures, with improved performance, such as rates, selectivity and lifetime and within lower cost process configurations. Catalysis does not change the thermodynamics of the catalysed process.

FIGURE 3

Catalysis overview

Catalysts provide alternative routes for reactions to proceed that would otherwise not take place. The overall energy change for the catalysed and uncatalysed reactions remains the same; however, the catalyst lowers the energy barrier for the reaction ('activation energy'), thereby increasing the rate of reaction so that chemical equilibrium is attained[28]. The diagram illustrates the case where high energy reactants are converted into more stable products, for example, the conversion of hydrogen and carbon dioxide into an alkane and water[29]. In this case, energy would be required to produce the hydrogen.



A key challenge is to develop catalysts allowing carbon dioxide to be used to produce mega-tonne scale products. The aim would be to increase the small pool of only 10 to 15 catalyst families deployed at world scale for chemicals manufacture. Catalysis is an industry where the UK has considerable strength (see Textbox 4). There is a major opportunity for the UK to build on these earlier successes to again lead the development of new catalysts and own their intellectual property and licensing that would have applications worldwide.

Most established catalysts use hydrogen and thermal energy to convert carbon dioxide. There are a set of inter-related processes being researched that use electrical or solar energy for the conversion of carbon dioxide and water either directly into fuels or syngas for further processing as found in the Fischer Tropsch process. The products made by these photochemical, electrochemical and photo-electrochemical processes are known collectively as solar fuels or artificial photosynthesis. Semi-conductor technologies and catalysis are at the heart of these approaches which are also of key importance in the generation of non-fossil derived renewable hydrogen which can be generated by solar water splitting.

4.2 The need to produce green hydrogen

In many of the uses described in chapter three hydrogen is needed as a feedstock to drive the conversion of carbon dioxide. Steam methane reforming of natural gas is the most common method of commercially producing hydrogen at industrial scale. Sustainable production of hydrogen ('green hydrogen') from non-fossil resources is needed to reduce overall carbon dioxide emissions for example in areas such as fuel cells and transport. The relative value of hydrogen in these areas could drive economies of scale and increase availability of hydrogen which could then be exploited in other other applications including uses of carbon dioxide[30]. The Royal Society is considering exploring the science of green hydrogen production.

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[26] Müller K, Mokrushina L, Arlt W. 2014 Thermodynamic Constraints for the Utilization of CO_2. *Chem. Ing. Tech.* **86**, 497-503 (doi:10.1002/cite.201300152).

[27] Miguel C *et al*. 2015 Direct CO_2 hydrogenation to methane or methanol from post-combustion exhaust streams – A thermodynamic study. *J. Nat. Gas. Sci. Eng.* **22**, 1-8 (doi:10.1016/j.jngse.201411010).

[28] Styring P, Quadrelli E. & Armstrong K. 2015 *Carbon Dioxide Utilisation: Closing the Carbon Cycle*. Oxford: Elsevier.

[29] *Op. cit.*, note 26.

[30] Smith *et al*. 2017 H2FC SUPERGEN: The Economic impact of hydrogen and fuel cells in the UK: a preliminary assessment based on analysis of the replacement of refined transport fuels and vehicles. See: http://www.h2fcsupergen.com/wp-content/uploads/2015/08/J5214_H2FC_Supergen_Economic_Impact_ES_WEB.pdf

TEXTBOX 4

UK successes in catalysis development and commercialisation

The global methanol industry generates approximately $55 billion in economic activity each year. Approximately 90% of the world's methanol is used in the chemical industry and around 10% is used as an energy feedstock. The first plant for processing synthetic methanol was started by BASF in 1923 and, over the following decades, a series of plants with capacities of 100 to 500 tonnes per day were operating in the USA. In the early years catalysts based on zinc oxide and chromia were used. In 1962 ICI filed a patent for a step change technology which was the Low Pressure Methanol process. In 1966 it commissioned the first plant based on this novel technology in which methanol is produced over a copper zinc oxide and alumina based catalyst via a multi-step chemical conversion. Today this process, catalyst technology and knowhow resides with Johnson Matthey, a UK listed company, and successive generations of catalysts have been developed to give increasing activity, selectivity and stability. Use of this low pressure methanol technology is the cornerstone of the global methanol industry and Johnson Matthey is now the world's leading supplier of methanol technology and catalysts. In collaboration with academic groups around the world, Johnson Matthey has on-going development programmes.

4.3 Sources of low carbon energy to drive the chemical conversion of carbon dioxide

Manufacturing synthetic fuels and chemicals and materials requires energy to drive the chemical conversion of carbon dioxide. To achieve net reductions in carbon dioxide emissions that energy needs to be low carbon. Alternatively, solar energy could be harnessed to react carbon dioxide electrochemically, mimicking photosynthesis. More research is needed to overcome current limitations, especially increasing the efficiency of capturing and harvesting solar energy. The Royal Society is considering exploring this.

4.4 Process engineering

Advances in chemistry will need to be complemented by advances in process and reaction engineering and novel process design. Close co-operation in science, development and commercialisation must continue.

4.5 The need for research partnerships

The challenges facing different uses of carbon dioxide may require a targeted approach to make the best collective use of the UK's world leading expertise in the fundamental science of catalysis and downstream carbon dioxide chemistry. Collaborations are important between disciplines across natural sciences and engineering, ranging from areas, such as materials discovery, molecular design, catalysis, biotechnology, analytical and spectroscopic science, membrane science, reaction engineering and systems science. Existing research networks could be applicable[31,32]. Collaborations are also important between academia and industry, as well as across sectors and markets. The scale of these scientific hurdles means that the UK will not solve them alone, creating the opportunity for international research partnerships with other leading countries.

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31. Solar Fuels Network. The Solar Fuels Network. See: http://solarfuelsnetwork.com/about/ (accessed 23 February 2017).

32. CO_2 Chem. About CO_2 Chem. See: http://co2chem.co.uk/ (accessed 23 February 2017).

Developing the commercial potential for using carbon dioxide

5.1 The need for broader analyses

Tackling climate change requires locking up carbon dioxide on geological timescales of tens of thousands of years. Various uses of carbon dioxide may lock up carbon dioxide on much smaller timescales, such as months or decades. Synthetic fuels can act less as a means to capture carbon dioxide and more as a means to transfer low-carbon energy into the sectors that need these fuels, where there is no current alternative to hydrocarbon fuels, since carbon dioxide will be emitted when these fuel are combusted. Carbon dioxide can be potentially locked away for longer periods in non-degradable polymers. The impact of the duration of carbon dioxide storage on climate needs to be better understood.

Life cycle analyses (LCA), including the thermodynamics and economics, are needed to understand the net contribution of specific uses of carbon dioxide[33]. Critical aspects include:

- the energy inputs required,
- the alternative uses for these energy inputs;
- the sources of carbon dioxide being used.

Any use of carbon dioxide needs to be an effective use of these resources compared to the alternatives from the perspectives of both cost and greenhouse gas emissions. One of the most comprehensive reviews in the research literature analysed 16 LCAs for carbon dioxide uses, and made various recommendations for future LCA research[34]. The possible economic effects of large-scale carbon dioxide use still remain unclear and more research on economic impacts is also needed[35].

These wider considerations can change over time due to changing socio-economic and other factors. LCAs should therefore be iterative and not detract from the need to explore new scientific opportunities.

5.2 The need for demonstration facilities

The UK lacks capability in scale up and prototyping in this area. Apart from a limited supply in Sheffield, it is difficult to access real carbon dioxide sources for such prototyping. Demonstration facilities for flue gas from sources, such as steel and cement works, and biomass processing plants, such as ethanol fermentation, would be beneficial to UK research on carbon dioxide use.

Demonstrators are needed to test technologies and explore whether they can become commercially viable at large scale. Port Talbot Steelworks has offered to become a national demonstrator for various carbon dioxide uses as set out in Textbox 3. Such demonstrators can encourage companies to invest resources in the UK by offering companies access to capabilities to support a future low-carbon infrastructure in key process industries including the supply chain partnerships.

> Life cycle analyses (LCA), including the thermodynamics and economics, are needed to understand the net contribution of specific uses of carbon dioxide.

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33. Von Der Assen N, Jung J, Bardow, A. 2013 Life cycle assessment of carbon dioxide capture and utilisation: avoiding the pitfalls. *Energy. Environ. Sci.* **6**, 2721-2734 (doi:10.1039/C3EE41151F).

34. Cuéllar-Franca R, Azapagic A. 2015 Carbon capture, storage and utilisation technologies: a critical analysis and comparison of their life cycle environmental impacts, *Journal of CO_2 Utilisation.* **9**, 82-102 (doi.org/10.1016/j.jcou.2014.12.001).

35. *Op. cit.*, note 6.

Conclusions

6.1 Using carbon dioxide to help decarbonise the UK's economy

Significant carbon dioxide emissions emanate from power generation, combustion of fuels and process industries (see Table 1). Power generation could be decarbonised by using non-fossil sources and applying carbon capture and storage to the fossil sources that may still be needed, such as natural gas. Some sectors, such as aviation, marine and long-range haulage, are hard to decarbonise and require liquid fuels. These liquid fuels ideally need to be derived from low-carbon sources. Where carbon dioxide is used it needs to be transformed with low carbon sources of energy as well as green hydrogen.

Process industries, such as cement, steel and chemicals, currently have irreducible carbon dioxide emissions as it is difficult for them to switch to low-carbon energy sources. From a lifecycle perspective, these emissions are a more attractive source of carbon dioxide than from power generation. They also offer an alternative source of carbon in place of sustainable biomass for fuels and chemicals manufacture. Industrial carbon dioxide storage and use has been considered in the development of industrial decarbonisation plans for eight energy intensive process industries of the UK[36]. The chemicals sector views using carbon dioxide to be important to the future of the UK chemicals industry because it can reduce the carbon footprint of the sector (subject to full life cycle assessments) by providing an alternative low-carbon feedstock for chemicals production. This will be important to secure jobs and growth in the chemical manufacturing regions around the UK if the industry is to move to a low-carbon future. This highlights how using carbon dioxide is now being seriously considered as a commercial proposition because decarbonisation is a key challenge for process industries.

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36. BEIS (Department for Business Energy & Industrial Strategy). 2015 Industrial decarbonisation and energy efficiency roadmaps to 2050: cross sector summary. See: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/419912/Cross_Sector_Summary_Report.pdf (accessed 27 February 2017).

6.2 Using carbon dioxide to deliver economic opportunities for the UK

The uses of carbon dioxide can be classified into two types: those that involve hydrogen and those that do not. For the former, green hydrogen is needed. Large scale uses of carbon dioxide, for example to manufacture fuels and commodity chemicals, will require significant amounts of green hydrogen. For uses that do not involve hydrogen, such as manufacturing polymers and mineral carbonates (see section 3.2), the scale of carbon dioxide used is smaller but can offer higher value[37,38].

Uses of carbon dioxide offer economic opportunities for the UK over a range of timescales: uses that that do not involve hydrogen could be adopted earlier than those uses that that do, aligning with transition to a reduced fossil fuel world. These opportunities align well with UK research and industrial capabilities and meet the Governments' plans for a 'low-carbon and resource-efficient economy'[39]. It represents an opportunity to 'cultivate a world-leading sector' that capitalises on cross-disciplinary supply chains well-represented in the UK and ensures their long term competitiveness for future investment[40].

Uses of carbon dioxide offer economic opportunities for the UK over a range of timescales

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37. CGSG (Chemistry Growth Strategy Group). 2013 Britain's chemical and chemistry using industries: strategy for delivering chemistry-fueled growth of the UK economy. See: http://www.cia.org.uk/Portals/0/Documents/Growth%20Strategy%20FINAL.PDF (accessed 27 February 2017).

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39. HMG (Her Majesty's Government). 2017 Building our industrial strategy: green paper. See: https://beisgovuk.citizenspace.com/strategy/industrial-strategy/supporting_documents/buildingourindustrialstrategygreenpaper.pdf (accessed 2 February 2017).

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Acknowledgements

This policy briefing is based on discussions from a workshop held at the Royal Society on 25 January 2017 and subsequent input. The Royal Society would like to acknowledge the contributions from those people who attended the workshop, as well as from a few people who did not attend, and helped draft and review the policy briefing (without necessarily endorsing it).

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ISBN: 978-1-78252-267-6
Issued: May 2017 DES4801