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Technologies and infrastructures underpinning future CO_2 value chains: A comprehensive review and comparative analysis

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ABSTRACT

In addition to carbon capture and storage, efforts are also being focussed on using captured CO_2, both directly as a working fluid and in chemical conversion processes, as a key strategy for mitigating climate change and achieving resource efficiency. These processes require large amounts of energy, which should come from sustainable and, ideally, renewable sources. A strong value chain is required to support the production of valuable products from CO_2. A value chain is a network of technologies and infrastructures (such as conversion, transportation, storage) along with its associated activities (such as sourcing raw materials, processing, logistics, inventory management, waste management) required to convert low-value resources to high-value products and energy services, and deliver them to customers. A CO_2 value chain involves production of CO_2 (involving capture and purification), technologies that convert CO_2 and other materials into valuable products, sourcing of low-carbon energy to drive all of the transformation processes required to convert CO_2 to products (including production of hydrogen, syngas, methane etc.), transport of energy and materials to where they are needed, managing inventory levels of resources, and delivering the products to customers, all in order to create value (economic, environmental, social etc.).

Technologies underpinning future CO_2 value chains were examined. CO_2 conversion technologies, such as urea production, Sabatier synthesis, Fischer-Tropsch synthesis, hydrogenation to methanol, dry reforming, hydrogenation to formic acid and electrochemical reduction, were assessed and compared based on key performance indicators such as: CAPEX, OPEX, electricity consumption, TRL, product price, net CO_2 consumption etc. Technologies for transport and storage of key resources are also discussed. This work lays the foundation for a comprehensive whole-system value chain analysis, modelling and optimisation.

1. Introduction

Carbon dioxide is widely accepted as a major cause of climate change: its accumulation in the atmosphere is a major contributor to the enhanced greenhouse effect [1]. Vast population growth and technological advancement, powered by fossil fuel exploitation, have resulted in a 68% increase in atmospheric carbon dioxide concentrations, compared to pre-industrial levels [2,3]. As a result of these increases in greenhouse gasses such as CO_2, a recent study by Gaffney et al. [4] estimates that anthropogenic emissions are causing climate change at a rate 170 times that of natural forces. Given the extensively detrimental environmental and socio-economic impacts this has been shown and predicted to cause, there has been a great amount of global interest in how best to reduce or reverse increasing atmospheric CO_2 levels. Recent initiative developments such as the EU Emissions Trading Scheme (EU ETS) increase the economic appeal of reducing carbon emissions. In the UK, the Climate Change Act 2008 sets out to achieve an 80% reduction in greenhouse gas (GHG) emissions by 2050 [5], while globally, treaties such as the Kyoto Protocol and the Paris Agreement identify reduction in carbon emissions as vital in preventing the potentially disastrous effects of further global warming [6].

In the UK, renewable energy and carbon capture and storage (CCS) have been identified as key technologies that can help achieve energy and emissions targets, alongside gas, low-carbon transport fuels, nuclear power and energy efficiency [7]. With CCS, CO_2 emissions are prevented from reaching the atmosphere by a dedicated capture

Abbreviations: CAPEX, Capital expenditure; CCS, Carbon capture and storage; CCU, Carbon capture and utilisation; CtL, Coal-to-Liquid; DME, Dimethyl ether; FT, Fischer Tropsch; GtL, Gas-to-Liquid; HHV, Higher heating value; HTFT, High-temperature Fischer-Tropsch; HVAC, High-voltage alternating current; HVDC, High-voltage direct current; IPCC, Intergovernmental Panel on Climate Change; LHV, Lower heating value; LTFT, Low-temperature Fischer-Tropsch; MtG, Methanol-to-Gasoline; MtO, Methanol-to-Olefins; NTP, Normal Temperature and Pressure (293.15 K, 1 atm); OPEX, Operating expenditure; PtG, Power-to-Gas; RWGS, Reverse water-gas shift; SMR, Steam methane reforming; SNG, Synthetic natural gas; TRL, Technology Readiness Level; WGS, Water-gas shift

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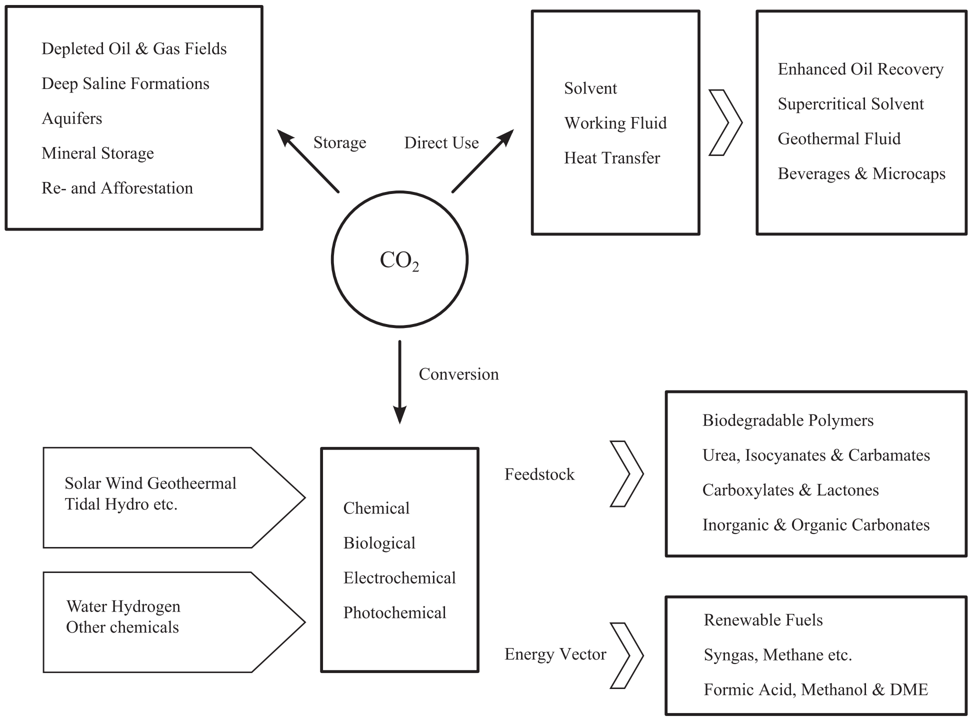

Fig. 1. Some of the possible pathways for CCU & CCS, adapted from Ref. [10].

technology, after which they may be separated from any associate emissions, transported and then stored, most commonly in deep underground formations. Despite its attractive potential as a climate change mitigation option, the high costs of CCS, combined with its technological immaturity and concerns of leakage, have somewhat hindered its large-scale global implementation so far, with the UK government recently axing a planned £1 billion prize for research into the technology [8]. An option that is potentially more attractive in some respects, but may also be complimentary to CCS, is Carbon Capture and Utilisation (CCU). In CCU, the captured CO_2 is used or converted into valuable products, as shown in Fig. 1. However, like CCS it includes some immature technologies and other concerns, such as high energy requirements for conversion, which must be overcome before it can be offered as an instrument in the battle against global warming. Despite the challenges they face, CCU and CCS are still seen to be vital for the future of our planet. According to the Intergovernmental Panel on Climate Change (IPCC) [9], the costs of climate change mitigation could increase by 138% without these technologies, and achieving the internationally agreed goal of limiting global temperature increases to 2 °C may be impossible without them.

In parallel with targets to reduce CO_2 emissions, many global and local policy makers are recognising the huge potential of renewable energy as a power source of the future. Inherent sustainability, increasingly attractive costs and significantly reduced environmental impacts compared to conventional fuels are some of the advantages of renewables. However, renewable electricity production also faces several challenges: as well as their low supply capacities at present, many of the technologies, such as solar and wind power, may be dependent on unpredictable and inconsistent weather conditions. This results in intermittency and variation in electricity outputs, which may obstruct the matching of supply with demand. Producing value-added products from CO_2 in processes powered by excess renewable energy offers benefits, both in reducing carbon emissions and increasing the penetration of renewables into countries' energy and chemical industries. Fig. 2 shows the magnitude and location of potential sources of CO_2, from various industries and power generation, that can be captured in the UK, indicating supply opportunities for CCU installations.

For CO_2 utilisation, it is crucial to examine the wider system of how to convert low-value resources into high-value products at a sufficiently large scale that makes the venture worthwhile. This will involve looking at network of technologies and infrastructures (such as conversion, transportation and storage) along with its associated activities (such as sourcing raw materials, processing, logistics, inventory management, waste management) required to convert low-value resources to high-value products and energy services and deliver them to customers. A CO_2 value chain involves production of CO_2 (involving capture and purification), technologies that convert CO_2 and other materials into valuable products, sourcing of low-carbon energy to drive all of the transformation processes required to convert CO_2 to products (including production of hydrogen, syngas, methane etc.), transport of energy and materials to where they are needed, managing inventory levels of resources, and delivering the products to customers, all in order to create value (economic, environmental, social etc.).

This study identifies and maps out the possible conversion pathways and technologies for CO_2 utilisation. The working principle of each technology is explained. The technologies are compared based on their technical, socio-economic and environmental advantages and limitations, with the aim of identifying which technologies can offer the most promising investment opportunities for meeting energy demands and emissions targets. Each technology is classified according to its Technology Readiness Level (TRL), which is a measure of its maturity – from basic observable principles through to fully operational chemical processes. In this work, the European Commission classification for TRLs [12] has been adopted, which is based on a scale from 1 to 9, as defined in Table 1. Along with TRLs, the technologies are also compared based on their gate-to-gate[1] key performance indicators (KPIs), such as capital expenditure (CAPEX), operating expenditure (OPEX), product price, net utilisation of carbon dioxide and energy requirements. Where available, other metrics, such as water consumption and plant operational lifetime, are also provided. For a meaningful comparison, cost data reported earlier than 2017 are adjusted to present values using the Chemical Engineering Plant Cost Index (CEPCI)

[1] Meaning the properties of materials leaving the facility relative to those entering it.