The carbon reuse economy as an enabler of a low-carbon future

The VTT Technical Research Centre of Finland has produced a discussion paper entitled: *'The Carbon Reuse Economy: Transforming CO_2 from a pollutant into a resource. MechChem Africa* presents the introductory chapter.

In a future world that has achieved the goals of the Paris Agreement, society will be largely free of fossil- and carbon-based goods and services. Fossil carbon in commodities will have been replaced by sustainable carbon cycles. For industrial energy supply, a shift from fossil fuels to electricity and electrolytic hydrogen will have taken place, while transportation will rely on a combination of battery-powered electric vehicles and sustainable hydrocarbon fuels.

However, a low-carbon world is not a no-carbon world as carbon will continue to be crucial for consumer commodities based on organic chemicals and materials as well as for food and animal feed. The required carbon will not be taken from fossil resources, however, but either from biomass or via the capture and reuse of the carbon content of various waste streams and end-of-life products.

Carbon capture and utilisation (CCU) is likely to begin with the utilisation of the most significant industrial point sources of CO_2, such as emissions from the cement and steel industries. After these industries have been electrified and decarbonised, capture will move towards biogenic sources. Finally, in the special case where point sources cannot provide sufficient carbon, the capture of CO_2 directly from air (direct air capture, DAC) will be realised. Carbon cycles in a future society are illustrated in Figure 1.

The Paris Agreement's goal is to mitigate climate change by keeping the global temperature rise well below 2.0 °C above pre-industrial levels and pursue limiting the temperature increase even further to 1.5 °C. In addition, the agreement takes into account the impacts of climate change and the measures needed to deal with them.

Despite the shift towards electrification, many major segments in industry and transport are expected to remain reliant on carbon-based fuels and commodity chemicals for the foreseeable future. However, blast furnaces in steel manufacturing may shift from using coke to using hydrogen as the reducing agent, enabling decarbonisation of this sector. In the cement industry a shift to either biomass or electricity to power rotary kilns is expected.

Furthermore, carbon capture and storage (CCS) and CCU could offer significant opportunities to reduce carbon emissions in these sectors. While CCS has been seen as a critical component in driving down emissions from fossil fuel use, CCU can be understood as an indirect electrification strategy for situations where direct electrification is either technically impossible or prohibitively expensive. Carbon is usually captured from the exhaust gases of thermal power generators in industrial processes like cement and steel plants, or biogenic CO_2 from bioenergy production. In the most widely proposed application of CCU, electrical energy is converted into chemical energy via electrolysis of water to produce hydrogen, while CO_2 is used to chemically bind the hydrogen produced into an easily storable or applicable form. There are two important parallels for such carbon reuse strategies:

- **The hydrogen economy:** The competition between the hydrogen (H_2) economy and the carbon reuse economy is a competition between developing a new distribution and use infrastructure for H_2 or capturing CO_2 and synthesising hydrogen-containing molecules that are compatible with existing infrastructure. They both need a renewable primary energy source, as the underlying difference is only related to the energy carrier and the infrastructure needed for that.
- **Waste hierarchy:** The principle of a waste hierarchy is to extract maximum benefits from products while minimising the amount of waste or preventing waste from being generated at all. Similarly, in the carbon reuse economy the principle is to reutilise carbon in a way that enables the decoupling of products and services from underground fossil carbon reserves. Figure 2 illustrates the relationship between more traditional climate mitigation options (energy conservation, energy efficiency and low-carbon technologies) and the various options available under Carbon Capture Utilisation and Storage (CCUS). Once CO_2 is captured it can either be stored underground (CCS) or reused for a range of purposes, from fuel (electrofuels) and chemical production to enhanced hydrocarbon or commodity recovery. The worst environmental outcome is also the cheapest, namely venting CO_2 into the atmosphere.

In addition to indirect electrification in the transport and energy sector, most organic chemicals and polymers such as plastic products and synthetic textile fibres required today could be produced from carbon dioxide. Common large-scale chemical intermediates such as methanol, ethylene, propylene and BTX (benzene, toluene, xylene) aromatics, which are important building blocks for sustainable end products, can be synthesised from carbon dioxide and hydrogen. Polymers and materials with significantly longer lifetime than, for example, fuel products can play an important role as carbon-binders through CCU. However, realising this vision will require significant renewal across the petrochemical industry.

The drivers for bulk energy products and high-value chemicals and materials are different. The market drivers for energy and fuel products are mainly based on the need for new sustainable fuels as a result of legislative pressures such as various mandates and subsidies. For example, fuels based on CCU and low-carbon electricity (electrofuels) are included in a new EU Directive on the promotion of the use of energy from renewable sources (RED II)[3] as a new class of sustainable fuels (liquid and gaseous renewable fuels of non-biological origin). Production of chemicals and materials is based mainly on the higher market value of these products compared to fuels providing better profitability. Even though the production cost of a CCU-based product is often higher than the cost of the displaced fossil-based product, the profitability of CCU can be improved by applying green premiums to the product price, improving the properties of a CCU-based product or the reputational enhancement that green products can provide.

Since the cost and supply of low-carbon energy are the main hurdles in the commercialisation of CCU products, it is easier to commercialise products that are less energy intensive to produce.

Some CCU applications exist where hydrogen is not needed, like the production of precipitated calcium carbonate, other carbonates and heat transfer liquids. Some organic products can be manufactured from CO_2 without hydrogen when raw materials are partially of fossil origin (polycarbonate polyols, polypropylene polyurethanes). However, due to the low share of carbon originating from CO_2 in these products, the positive climate impact is limited. Despite the limitations, these products can play an important role in the commercialisation of CCU technologies.

Furthermore, in some CO_2 conversion processes hydrogen demand is limited, or hydrogen can be applied to boost bio-based processes where CO_2 is released as a by-product. An example of such a process is the production of hydrogen-enhanced biofuels, where hydrogen is used to convert CO_2 formed as a by-product of biomass processing.4 However, in most CCU conversion processes the demand for hydrogen is high, meaning that significant cheap, low-carbon electricity capacity is required to cover the needs of high-volume production of CCU-based products.

From an overall systemic sustainability aspect, achieving carbon neutrality, and especially carbon negativity, requires careful optimisation of the capture and release of CO_2. This means balancing the usage (repository) between/within the short-term, mid-term and long-term commodities and storage. This in turn means that operations can be carbon neutral or carbon negative, but if they are not managed and optimised from a systemic perspective the impact on sustainability is difficult to determine.

Still, this fact does not constrain the use of CO_2 as a resource. For instance, in areas where agriculture is no longer viable owing to loss of arable land and scarcity of water, CO_2 plays a crucial role in the production of nutritious foods. In the long-term, however, utilisation of CO_2 needs to be based on low-carbon energy to help tackle climate change.

One fifth of human-caused greenhouse gas emissions originate from agriculture5, either directly from machinery fuels and farm animals, or indirectly as a consequence of land-use change. Modern agriculture also raises many other environmental concerns: over-fertilisation has led to eutrophication of water ecosystems, and depletion of biodiversity is also a serious problem, as is the sufficiency of natural resources such as water, soil and forests.

At the same time, the need for food production is expected to grow by about 50% by 2050, while climate change threatens to reduce production by 50%. The potential to further increase the land area used for cultivation is limited, as today 50% of habitable land area is already used for fields and only 37% for forests.6 In a future society, fields and animals will not serve as the only source of human nutrition. Instead, biotechnical solutions will be used to produce food and feed with a smaller environmental footprint and with reduced land use requirements.

Food production can use either direct sunlight or even electricity (through hydrogen) as a source of energy.7 In both cases, microorganisms convert CO_2 into amino acids, carbohydrates, vitamins and lipids, provided that sustainable sources of nitrogen and phosphorus are available. The bacterial cell mass produced in such hydrogen fermentations contain, in addition to compounds with nutritional value, high amounts of feedstocks for the production of biodegradable plastics (polyhydroxyalkanoates) and biofuels (lipids).

The accumulation of reduced organic compounds in the biomass produced from hydrogen fermentation is indicative of a high biosynthetic potential of the microbial biocatalysts and means they can be engineered to enable the production of value-added organic compounds such as pigments, flavours and chemical feedstocks.

The three potential carbon reuse economy product pathways envisioned in this study are shown in Figure 3 and presented in Chapter 4 of this study. This, along with the references embedded in this article, can be accessed from the full study, which can be found at address below.

https://www.vtt.fi/Documents/uutiset/2019/190620_FINAL_WEB_VTT_CRE_Discussion_Paper_PAGES_display.pdf

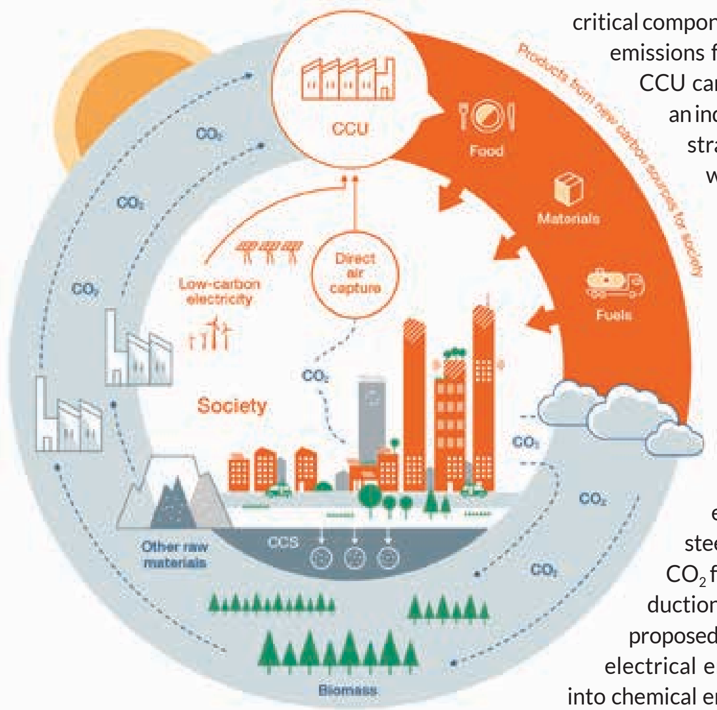

Figure 1: Carbon cycles in a future society.

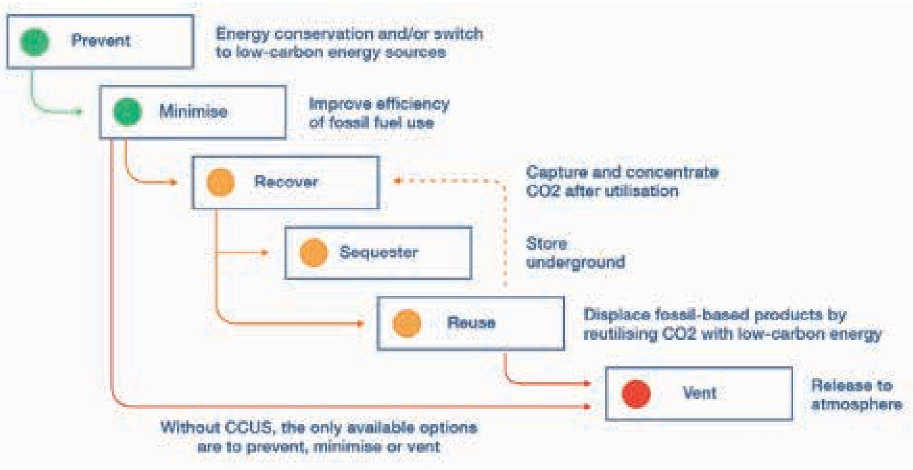

Figure 2: CCUS hierarchy according to Hannula and Reiner (2017).2

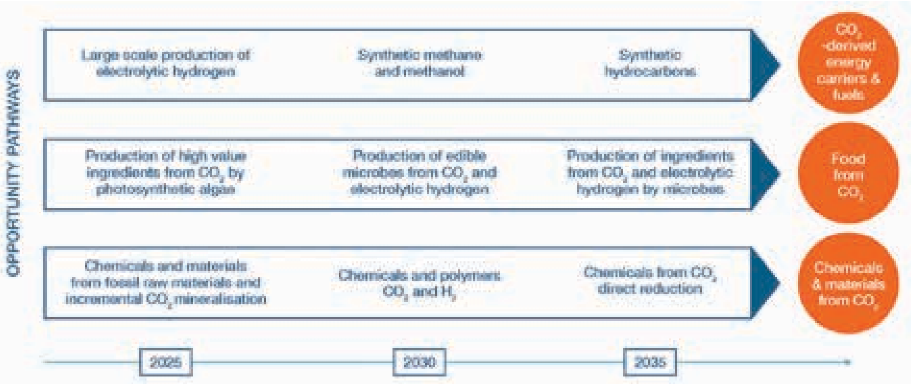

Figure 3: Carbon Reuse Economy pathways.