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Climate Change Mitigation:

The contribution of Carbon Capture and Utilisation (CCU)

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Abstract

Carbon Capture and Utilisation (CCU) is a broad term that covers processes that capture CO_2 from flue and process gases or directly from the air and convert it into a variety of products such as renewable electricity-based fuels, chemicals, and materials. No precise estimate of the potential mitigation role of CCU technologies exists to date, because of uncertainties in renewable electricity cost scenarios and the low granularity of models that simulate different CCU options.

However, CCU technologies have the potential to play a significant role in the mitigation of climate change as described, in the latest report of the Working Group 3 of the Intergovernmental Panel on Climate Change[1]. Many of the technologies are already mature enough to be deployed and have the potential to reduce net CO_2 emissions in gigatons equivalence CO_2 emissions. Unlike other options, CCU technologies provide drop-in fuel solutions which can be introduced in existing markets without significant modifications to powertrain production, distribution and infrastructures. CCU technologies have potential to provide solutions to hard-to-abate sectors and to generate revenues through the producion of marketable products. Moreover, CCU can help achieve an energy sovereignty and a reduced depedency on fossil fuels-based energy. Nevertheless, the slow deployment of CCU results from the low availability of renewable energy, the lack of market incentives and the absence of a favourable regulatory framework. The present work discusses the climate mitigation potential of CCU, including opportunities and limitations of CCU technologies from CO_2 mineralisation to power-to-X applications.

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has recently published its 6th Assessment[2] demonstrating that human activities have increased global temperature of 1.1 °C over the last centuries. Despite the development of climate policies and regulations, human-induced greenhouse gas (GHG) emissions have never been as high as they are today (Fig. 1). To keep climate change within 'manageable' limits, total global warming should not exceed 1.5°C. This implies::

- Inverting the emission trend by 2025
- Halving global GHG emissions by 2030
- Reaching climate neutrality by 2050

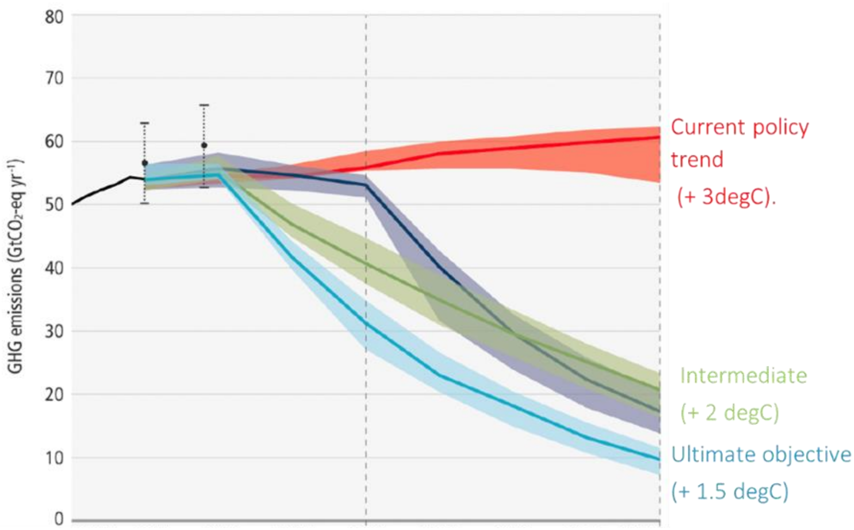

Figure 1: Global greenhouse emissions scenarios to 2050[2]

These objectives are highly challenging and will be reached only with drastic changes at all levels in the society, including all industrial sectors. Solutions to reach climate objectives exist today for all sectors but are not integrated in a systematic way. The following priorities are required to drastically reduce GHG emissions:

1) Sobriety (reducing the production and consumption of services and goods to our essential needs), efficiency in term of material and energy, and circularity.
2) Electrification of all processes that can be efficiently electrified on short- to mid-term.
3) Acceleration of the development of renewable and low carbon sources.
4) Creation of low carbon fuel solutions including biofuels and renewable electricity-based fuels (e-fuels) for sectors that cannot be electrified on the short-term.
5) Development of low carbon materials based on renewable feedstock.
6) Deployment of carbon capture solutions for unavoidable emissions. The CO_2 can then be stored underground or in materials.

To mitigate climate change, all possible solutions should be combined in the most efficient way to increase their impacts.

In addition to the reduction in GHG emissions, the IPCC[1] states that new investments on fossil carbon infrastructures are not compatible with climate objectives. Coal production should be completely phased out by 2050 and oil and gas plants should close prematurely. However, they also show with high confidence that carbon is a key building block in organic chemicals, fuels and materials and that it will remain important going forward. This means that there is an urgent need for significant development of renewable and low carbon energy sources, but also for alternative non-fossil carbon feedstock (e.g. CO_2/CO, biomass, recycled plastics). The creation of a circular carbon economy based on CCU is essential to move away from the fossil era and to reach climate targets. Below, we discuss the role of CCU in different sectors, its potential to mitigate climate change and its limitations.

2. Carbon Capture and Utilisation

CCU refers to processes in which CO_2 is captured and the carbon is then used in a product[1].The CO_2 can be captured from point sources or directly from the air and be converted into different types of products, such as building materials, e-fuels and chemicals (including plastics) (Fig. 2). Numerous CO_2 conversion technologies exist which can mainly be divided into two categories: the power-to-X and CO_2 mineralisation applications.

- Power-to-X is the concept enabling the production of e.g. fuels and chemicals by using electricity and CO_2 to replace fossil carbon. Indeed, water electrolysis provides hydrogen that reacts with captured carbon to produce all commonly used hydrocarbons. Two types of fuels can be generated: 1) Synthetic gas (e.g. e-methane) so-called Power-to-Gas and 2) Liquid fuels & chemicals (e.g. methanol, ethanol), so-called Power-to-Liquid. When renewable energy is used to produce hydrogen, these types of fuels are called renewable electricity-based fuels[3,4,5]. Different pathways exist to convert CO_2 into fuels, and chemicals, some are still in the laboratory, prototype, and pilot phases, while others have been fully commercialised (such as urea production)[6].

- The mineralisation of CO_2 is also referred to as carbonation, and is a natural phenomenon where, Ca (calcim)- or Mg (magnesium)-containing minerals react with CO_2 to produce calcium or magnesium carbonate ($CaCO_3$ or $MgCO_3$). Respectively, these are known as limestone or dolomite and form one of the most abundant rock types found at the Earth's surface. The carbonation reaction can be accelerated to take only a few minutes in a managed processes called 'accelerated carbonation. The latent reactivity of minerals found in solid waste can be readily reacted with dissolved CO_2 to form building materials (e.g., aggregates, concrete blocks etc.). The CO_2 is permanently captured in carbonated products and the technology is deployed at industrial scale[7,8,9,10,11].

In CO_2 conversion processes, CO_2 can be captured from point sources, whether fossil or biogenically derived, or directly captured from the air. The efficacy of CCU processes is influenced by CO_2 purity and pressure requirements. For instance, urea production requires CO_2 pressurised to 122 bar and purified to 99.9%. While most utilisation pathways require purity levels of 95-99%, e.g. algae production may be carried out with atmospheric CO_2[12,13] while CO_2 mineralisation does not need pure CO_2.

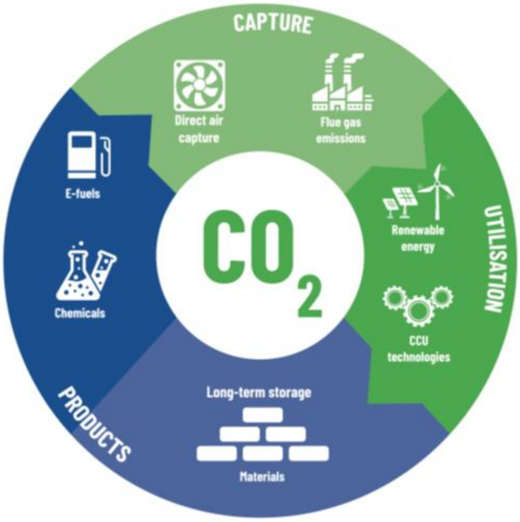

Figure 2: Schematic of the concept of Carbon Capture and Utilisation.

3. The role of CCU to mitigate climate change

To date, the concept of CCU is not considered in the Integrated Assessment Models used for climate projections. The reasons for ignoring CCU in these models are the uncertainties in renewable electricity cost scenarios and the low granularity of models to simulate the complexity of the different CCU options[14] (Detz and Zwaan, 2019). Consequently, no exhaustive quantification exists to date on the climate mitigation potential of CCU technologies, although various estimates have been reported for the quantities of CO_2 that could be re-used[15,16]. However, numerous modelling exercises have shown the efficiency of CCU applications, and the climate community now recognises the potential of CCU to move away from fossil resources, reduce net CO_2 emissions, and remove CO_2 from the air[1, 17]. Recently, Galinova et al. (2022)[18] have made an analysis of more than 100 scientific energy system analyses using renewable electricity-based CCU that may help to better assess the role of CCU in a renewable world. Depending on the context, CCU can allow reducing, avoiding or removing CO_2. These three concepts are crucial to reach climate objectives, but they do not have the same impact and should be assessed according to the context.

Table 1: Definitions of the different roles CCU can play to mitigate climate change.

Concept	Definitions	CCU impact
Net emission reduction	Reduction of the amount of CO_2 emitted to the atmosphere for a specific service or sector	CCU can provide net emission reduction when, e.g. CO_2 emitted from one service is captured and used to produce e-fuels for another service (Fig. 3, middle panel).
Emission avoidance	Avoiding the use of an emission-producing service entirely or shifting to the lowest-emission mode of providing the service.	CCU can avoid emissions when CO_2 emissions are stored durably in products or when CO_2 stays in a closed loop.
CO_2 Removal (CDR)	Anthropogenic activities removing CO_2 from the air and durably storing it away from the atmosphere.	CCU can provide CDR solutions when atmospheric or biogenic CO_2 is durably stored in products via mineralisation or other processes[19,20] when the captured CO_2 stays in a closed loop.

CCU is not linear solution as for example Carbon Capture and Storage (CCS). Therefore, it is crucial to understand its specific potential in each sector and for each type of applications as described below.

3.1. CCU in the energy system

To reach net zero emissions from the energy sector, fossil fuel-based energy demand should be mainly replaced by renewable electricity (RE)[21]. However, there are sectors such as aviation, shipping, heavy transportation, and energy intensive industries where hydrocarbons cannot easily be replaced by electricity, or physically not at all[16,22]. In the long term, net zero emissions could be achieved by a “defossilisation” of the energy system, whereby carbon from fossil sources is replaced by direct electrification where possible and for the remaining cases by carbon that is created synthetically and sustainably from CO_2 and RE via power-to-X, enabling the production of RE-based fuels. These fuels can be stored, transported and used as such or to produce electricity again. Liquid RE- based fuels are easier (and relatively inexpensive) to store and transport compared to electricity and can be used in most cases in existing infrastructures. Moreover, they can be stored at large-scale over extended periods, including in vehicle tanks, and can support the indirect balancing of the energy system and bring renewable energy to sectors that cannot use it directly[3, 4, 5, 22]. Artz et al., 2019[23] has shown that the largest reduction in the absolute amount of GHG emissions could be achieved by coupling of highly concentrated CO_2 sources from CO_2-emitting sectors with RE-based hydrogen.

Technologies to capture CO_2 from point sources and to convert it into RE-based fuels already exist and should enable in the near term to reduce CO_2 emissions from hard-to-abate sectors. But the long-term goal should be to close the loop, move away from fossil fuel and create net-zero emission processes (Fig. 3).

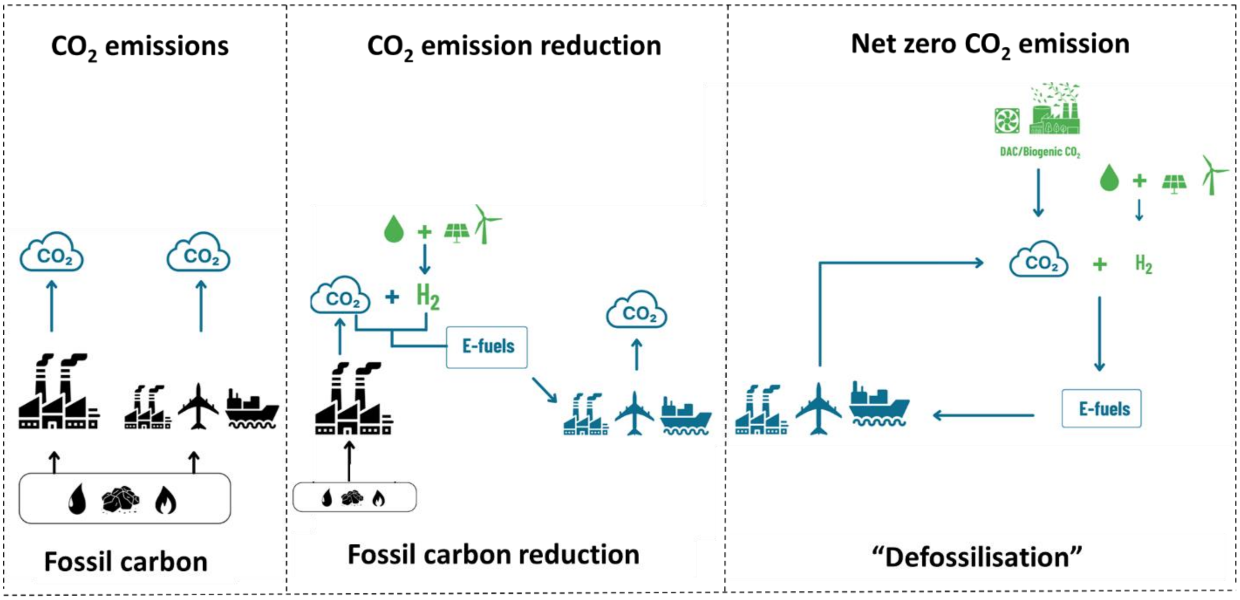

Figure 3: The role of CCU in the energy system (adapted from [24])

The long-term use of carbon-based energy carriers in a net zero emissions economy relies upon their production with RE for low-cost, scalable, clean hydrogen production for example via the electrolysis of water. The estimated potential for the scale of CO_2 utilisation in fuels varies widely, from 1 to 6.1 Gt CO_2 yr^{-1}, reflecting uncertainties in potential market penetration[16, 18, 21, 22].The high end represents a future in which synthetic fuels have sizeable market shares, due to cost reductions and policy drivers. The low end -which is itself considerable- represents a very modest penetration into the methane and liquid fuels markets, but it could also be an overestimate if CO_2-derived products do not become cost competitive with alternative clean energy vectors such as hydrogen or ammonia, or with CCS[5, 16, 25, 26].

3.2. CCU in the chemical industry

Carbon is a key building block in organic chemistry and will remain important as stated by the IPCC AR6 WG3 Chapter 11[1]. However, the production of chemicals involves massive use of fossil carbon and significant GHG emissions amongst which about 60 to 70% are embedded emissions[27]. To reach climate targets, the chemical sector should not only reduce its emissions, but it should also decouple chemical production from fossil resources by creating a circular carbon economy where renewable carbon circulates between biosphere, atmosphere and technosphere. Renewable carbon entails all carbon sources that avoid or substitute the use of any additional fossil carbon from the geosphere. There are three sources of renewable carbon at the surface of the Earth: captured carbon, biomass or recycled plastic[27].

CCU via Power-to-X allows bringing RE to the chemical sectors and to use captured carbon as a substitute to fossil carbon[28]. Kätelhön et al., 2019[29] demonstrate that the climate change mitigation potential of CCU in the chemical industry will not be dependent on the amount of CO_2 used in the process, but on the potential for substitution of conventional products. From a LCA perspective, they covered the 20 most GHG intensive chemicals in Europe and concluded that the technical mitigation potential of CO_2-based chemical production (i.e. technically feasible GHG reductions under full deployment of technologies) can be up to 3.5 Gt CO_2-eq by 2030. Technologies are already available to switch to CO_2 and water as substrates, but scale-up requires massive amounts of RE.

While several technological options exist for decarbonising the main industrial feedstock chemicals and their derivatives, the costs vary widely[1, 30]. Fossil fuel-based feedstocks are inexpensive and still without carbon pricing, and their biomass- and electricity-based replacements are expected to be more expensive. IEAGHG-2021 report[30] has demonstrated that the economic competitiveness of CCU routes is reliant on a ‘cost of emission’ being applied and for the optimal pathways considered, cost parity could be achieved in the long-term by implementing a cost of emissions between USD 120-225/tCO_2. Chemical industries consume large amounts of hydrogen, ammonia, methanol, carbon monoxide, ethylene, propylene, benzene, toluene, and mixed xylenes & aromatics from fossil feedstock. From these building blocks, tens of thousands of derivative end-use chemicals are produced. The IPCC AR6 WG3 Ch.11[1] states that hydrogen, CO_2 from biogenic origin or from the air, and collected plastic waste as primary feedstocks can greatly reduce the total emissions of the chemical sector. However, biogenic carbon feedstock might be used but is expected to be limited due to competing land-uses.

3.3. CCU in the building sector

The building sector is the most carbon intensive sector of the industry with about 8% of global CO_2 emissions coming from cement production, three-fourth of which are unavoidable as they are coming from embedded carbon. Urbanisation of the past decades has led to a significant increase in these emissions because of the amount of CO_2 released in the production of building materials. To reach climate neutrality, the Global Concrete and Cement Association Roadmap[31] has set 6 priorities:

- Replacing fossil fuels to fire the cement kilns
- Using RE for the indirect energy emissions
- Deploying Carbon Capture at scale
- Reducing the amount of clinker in cement and cement in concrete
- Recycling more concrete from construction and demolition waste
- Enhancing the level of CO_2 uptake in concrete through enhanced (re-)carbonation

Five out of six of these elements are related to CCU. Power-to-X enables to produce renewable fuels to replace fossil fuels to fire the cement kilns and to bring RE in the process[22], and mineralisation allows capturing and binding CO_2 permanently in building materials (as carbonates). Moreover, carbonate minerals can substitute for part of the cement in the concrete mix, reducing the overall carbon footprint of the final product[8,11].

Mineral wastes such as slags and ashes from the power and steel sectors or concrete from the demolition of old buildings are abundant sources of calcium that can be used in combination with CO_2 to create a wide range of construction materials, thereby also avoiding landfill costs. Because mineralisation utilises the latent chemical energy within solid waste, it offers a low energy/low cost route to mitigate GHG emissions. Because CO_2 is bound into solid carbonates, storage has a strong potential to be permanent and nontoxic[32]. Mineralisation enables both gaseous and solid waste to be recycled together (Fig. 4).

The deployment of LCAs has demonstrated that CCU technologies for mineralisation could reduce climate impacts over the entire life cycle based on the current state-of-the-art and today's energy mix. Up to 1 Gt per year of the cement market could be substituted by mineralised products[8, 10, 33].

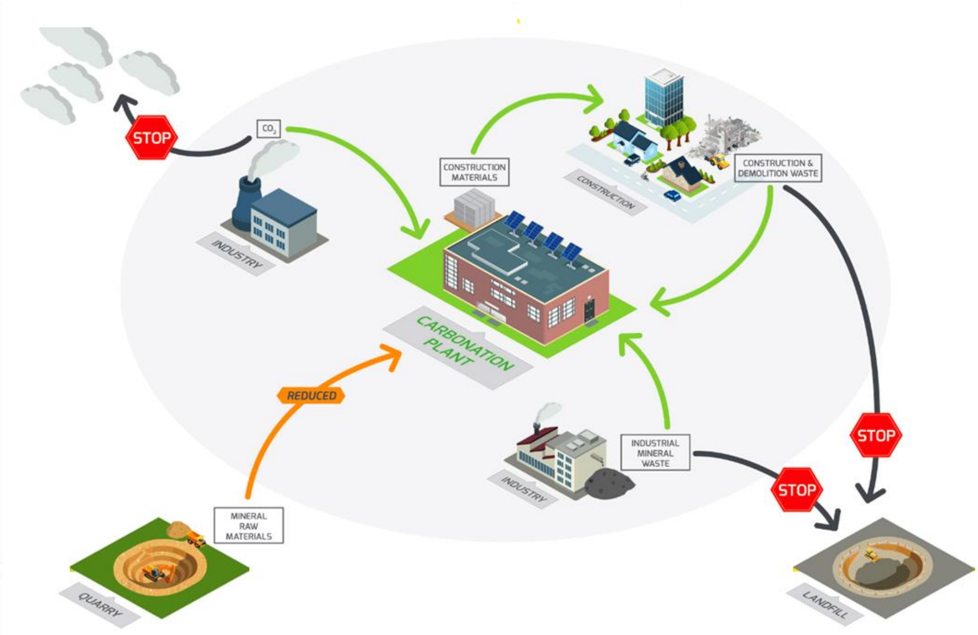

Figure 4: Concept of double circularity for gas and solid waste via CO_2 mineralisation.

4. How to assess the impact of CCU?

CCU is often seen both as a solution and as a distraction for deep climate mitigation targets because of the large diversity of CCU technologies and the complexity of assessing their potential role, benefits, bottlenecks and impact. Moreover, confusions exist between CCU and CCS despite their differences in CO_2 reduction potential, the underlying technical processes, applications and outcomes. The approaches are fundamentally different because CCS is a linear solution to decarbonise emissions and, CCU is an integrative circular solution to both reduce emissions, and to provide alternative feedstock in moving away from fossil resources.

Depending on CCU applications, the duration of the CO_2 stored in products can vary from days to millennia. This is often a topic of debate when assessing CO_2 reduction potential, because in some studies only technologies storing away CO_2 permanently are considered as compatible with climate targets[34]. This omits the key role of CCU which is not only to decarbonise emissions, but subsititute fossil-based products. Therefore, in term of environmental assessment, these technologies should not be assessed only with respect to the amounts of CO_2 that can be used nor to its storage duration, but rather it is essential to determine the full life cycle of the CO_2-based product generated and its benefits to society[35, 36]. If CCU products substitute for fossil-based products and provide the same or even a better service, the focus of LCAs should be on the cradle-to-gate[29]. Two important points should be highlighted[37, 38, 39]:

1) If CO_2-based products can be produced with less environmental impact (including GHG emissions) than fossil-based ones, an environmental benefit arises, independent of the CO_2 storage time within products.
2) If CO_2-based products are recycled at end of life, the embodied CO_2 emissions are recaptured in new products, and the duration of CO_2 storage is no longer crucial to LCAs.

In summary, the impact of CCU involves both direct and indirect CO_2 "savings" which should be assessed using a full and systemic LCA and the following elements should be considered:

- Source of carbon (DAC, biomass, fossil)
- Energy requirements (amount and source)
- Type of capture and conversion process
- Type of product and storage duration in the product
- The actual substitution effect (replacing or adding?)
- Public perception and acceptance related to CCU
- Market penetration of the product
- Geographic setting/industrial symbiosis

The diversification of methods to assess CCU's climate mitigation potential may hampers its development, therefore harmonised methodologies are crucial as described in the guidelines of the Global CO_2 Initiative[40].

5. Outlook

Despite the absence of an authoritative quantification of the mitigation potential of CCU technologies, the use of captured CO_2 as an industrial feedstock is one building block in a portfolio of climate mitigation measures[1, 14, 38, 41]. The capture and conversion of CO_2 into valuable products using RE sources is often considered as a drawback to use CCU. However, the future prices of the different RE (especially the cost of solar energy) is crucial to the viability and climate mitigation potential of CCU technologies[17, 42, 42, 44, 45]. CO_2 utilisation could directly contribute to reduced emissions with an estimated potential in the region of gigatons CO_2 equivalent. This potential is similar or even superior to the projected impact of CCS combined with biofuel productions but has a lower societal cost[46]. Moreover, the key role of CCU as a crucial vector to move away from fossil fuel dependency needs to be fully recognised[35, 47].

To conclude, the deployment of CCU enables:

- Drop-in solutions that have the potential to utilise up to 8 Gt of CO_2 per year by 2050, equivalent to approximately 20% of current global CO_2 emissions[16]
- The reduction and avoidance of CO_2 emissions whilst maintaining essential services historically based on fossil resources
- CO_2 removal solutions where atmospheric or biogenic CO_2 is permanently stored in products
- The indirect balancing of the energy system
- Renewable energy to sector that cannot use it directly
- The "defossilisation" of the chemical, energy and transport sectors
- Circularity and a reduced demand for non-circular raw materials

CCU-based technologies have the potential to provide significant emission savings for power and other industrial sectors through the substitution of fossil-fuel-based raw materials, thereby increasing efficiency and the use of renewable energy, and the generation of revenues through marketable products[16, 39].

Current "blocks" on the full-scale deployment of CCU include:

- The availability of low carbon electricity
- The demand for water, minerals and non-renewable materials for the capture and conversion processes
- The current immature international policy framework
- The difficulties to assess public (risk) perception of the CCU concept as a building block of a climate change mitigation strategy
- The local acceptance of the required technical infrastructure and the market acceptance of CO_2-based products[48]
- The conflicting expectations on the sociopolitical level regarding CCU and its association or not with CCS[37].

In conclusion, CCU technologies directly targets the cause of climate change via direct utilisation of climate-damaging emissions, but also on the main historical cause (by reducing industry dependence on fossil). The deployment of CCU technologies offers circular economic solutions for climate neutrality, via direct and indirect carbon savings in manufactured products which can store carbon for time periods considered permanent, or which can be recycled without stored carbon being lost. The wider integration of CCU-based manufacturing processes has potential to significantly contribute to the low-carbon economy and a consequent improvement in environment, climate and human health that can be quantified via full LCAs and environmental impact assessments.

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