No climate neutrality without creating a circular carbon economy

Pas de neutralité climatique sans la création d'une économie circulaire du carbone

Célia Sapart[1]

[1]Scientific Director, CO_2 Value Europe, celia.sapart@co2value.eu

ABSTRACT. For several decades, exponential growth in the use of fossil carbon has created drastic climate disturbances. To mitigate climate change, all uses of virgin fossil carbon must, urgently, be phased out. Many transport sources and industrial processes can easily be electrified and should be where possible. But some sectors like chemical, materials (e.g. lime and steel), aviation and maritime transport will continue to use carbon and the virgin fossil used today will need to be substituted to meet climate neutrality targets. Using CO_2 to replace fossil carbon in sectors that will still need hydrocarbons is a key solution to « defossilise » our economy. The concept of 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 fuels, chemicals, and materials. No precise global 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 (IPCC).

RESUME. Depuis plusieurs décennies, la croissance exponentielle de l'utilisation du carbone fossile a entraîné des perturbations climatiques considérables. Pour atténuer le changement climatique, toutes les utilisations de carbone fossile vierge doivent être supprimées de toute urgence. De nombreux moyens de transport et processus industriels peuvent facilement être électrifiés et devraient l'être dans la mesure du possible. Mais certains secteurs comme la chimie, les matériaux (par exemple la chaux et l'acier), l'aviation et le transport maritime continueront à utiliser du carbone et le carbone fossile vierge utilisé aujourd'hui devra être remplacé pour atteindre les objectifs de neutralité climatique. L'utilisation du CO2 pour remplacer le carbone fossile dans les secteurs qui auront encore besoin d'hydrocarbures est une solution clé pour "défossiliser" notre économie. Le concept de captage et d'utilisation du carbone (CCU) est un terme général qui couvre les processus de captage du CO2 dans les fumées et les gaz de traitement ou directement dans l'air et sa conversion en divers produits tels que des combustibles, des produits chimiques et des matériaux. Il n'existe à ce jour aucune estimation globale précise du rôle potentiel d'atténuation des technologies CCU, en raison des incertitudes liées aux scénarios de coûts de l'électricité renouvelable et de la faible granularité des modèles qui simulent les différentes options CCU. Cependant, les technologies CCU peuvent jouer un rôle important dans l'atténuation du changement climatique, comme le décrit le dernier rapport du groupe de travail 3 du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC).

Keywords. Defossilisation, Circular Economy, Carbon Capture and Utilisation.

Mots-clés. défossilisation, économie circulaire, stockage et utilisation du carbone.

Introduction

In this contribution, we discuss the concept of « defossilisation » using CCU and its role as climate mitigation solution, but as well the opportunities, challenges and limitations related to the deployment of these technologies. While a few studies show that CCU technologies have the potential to utilise CO_2 at a few gigaton per year by 2050, we are presenting the results of a first-of-a-kind qualitative assessment on the contribution of CCU to reach climate neutrality in Europe. Our results show that at least 21% of emissions reduction achieved through technological solutions in the EU will come from CCU and that it will play a crucial role in the industry and transport sectors. Unlike other options, these technologies provide drop-in 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 production of marketable products. Moreover, CCU can help increasing energy sovereignty and reducing dependency 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 consistently favourable regulatory framework.

1.Background

For several decades, exponential growth in the use of fossil carbon has created drastic climate disturbances at global scale. As shown by the scenarios of the Intergovernmental Panel on Climate Change [IPCC, 2022] and of the International Energy Agency [IEA, 2023], the only way to reach climate neutrality is to drastically decrease greenhouse gas emissions, but also to urgently phase out coal, oil and gas. Many transport sources and industrial processes can easily be electrified and should be where possible. But some sectors like chemical, materials (e.g. lime and steel), aviation and maritime transport will continue to use carbon and the virgin fossil used today will need to be substituted to meet climate neutrality targets.

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) [RCI, 2022].

Here, we focus the discussion on the utilisation of captured carbon as feedstock for the creation of a circular carbon economy. This concept of Carbon Capture and Utilisation (CCU) is essential to move away from the fossil era and to reach climate targets [SAP, 2022] [CO2, 2024].

2. The concept of Carbon Capture and Utilisation

CCU represents a large set of technologies in which carbon is captured and used to produce essential products. Carbon is usually captured from concentrated industrial waste gases in the form of carbon dioxide (CO_2) or, sometimes carbon monoxide (CO). CO_2 can also be captured from the air in a process known as direct air capture (DAC). The captured carbon can then be converted into different types of products that have traditionally been made from fossil carbon sources, such as building materials, synthetic fuels and chemicals (Fig.1).

CCU is recognized by the IPCC [IPCC, 2022] as a climate-mitigating solution to carbon-intensive sectors e.g., process industry, aviation, maritime and construction, where no or very few alternatives exist to reduce emissions and move away from fossil resources. These solutions should not substitute large-scale efforts to prevent greenhouse gas emissions especially when more energy-efficient solutions are available, but they should be seen as significant opportunities to reduce emissions and increase circularity in sectors that will continue to be reliant on carbon-based feedstock and fuels [KAT, 2019]. Moreover, to ensure real emission reductions over their entire value chain, the climate-mitigation potential of CCU technologies should be based on a full life-cycle analysis [GCI, 2022].

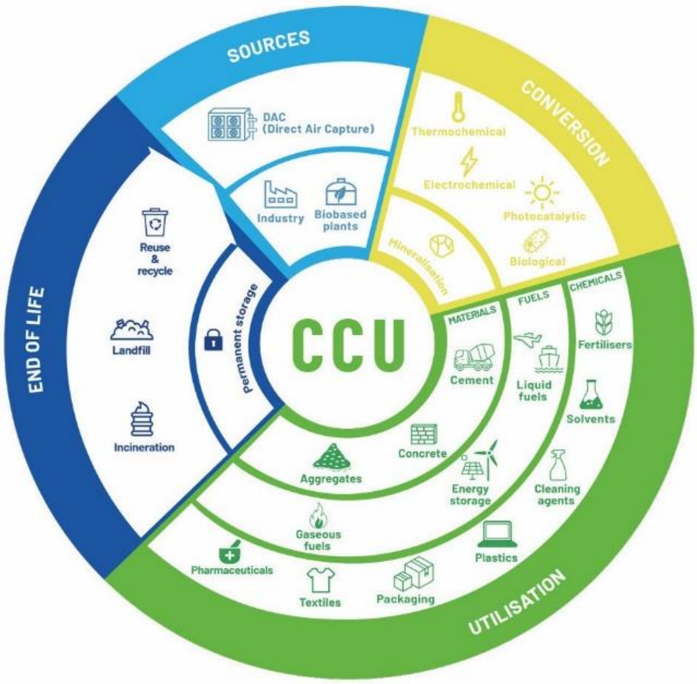

Figure 1: The concept of CCU [CO2, 2024]

Numerous CO_2 conversion technologies exist and are at different stages of development including some that are already commercialized [BUS, 2018]. They can mainly be divided into two categories:

- The production CCU fuels and chemicals by using renewable/recycled H_2 and captured carbon to produce hydrocarbons which substitute fossil equivalents [MER, 2023] [IEA, 2021] [AMP, 2015]. H_2 can be produced by water electrolysis using renewable or low carbon electricity (i.e. the Power-to-X approach), or recycled from industrial processes, and reacts with captured carbon to produce all commonly used hydrocarbons. Liquid and gaseous fuels and chemicals can be generated using these different types of processes (e.g. biological, thermochemical, electrochemical, photocatalytic, etc.). Some processes under development aim at bypassing the production of H_2 as intermediate and react captured carbon directly with water. When the energy carrier of CCU products is of renewable origin (other than biomass) then this type of products is referred to as Renewable Fuels of Non-Biological Origin (RFNBO); when the energy is already present in the recycled streams then they are referred to as Recycled Carbon Fuels (RCF).

- The mineralisation of CO_2 is also referred to as carbonation and is a natural phenomenon sequestering CO_2 on geological timescales in rocks. (Ca (calcium)- or Mg (magnesium)-containing minerals react with CO_2 to produce carbonates ($CaCO_3$ or $MgCO_3$). Respectively, these are known as limestone or dolomite and form one of the most abundant rock types found on 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.) where CO_2 is permanently stored.

3. The climate mitigation potential of CCU technologies

CCU technologies have existed for several decades, such as in the production of urea, but only started to be seriously considered as a potential solution to mitigating climate change in the last decade. In recent years, there has been an exponential technological evolution and recognition.

To date, no exhaustive quantification exists on the global climate mitigation potential of CCU technologies, because of the uncertainties in the evolution of renewable electricity availability and cost and because of the low granularity of models to simulate the complexity of the different CCU options [SAP, 2023] [CO2, 2024] [DETZ, 2019]. One challenge is that CCU is often assessed in a linear way [DEK, 2019] only considering its decarbonisation potential, while the main objective of these large set of technologies is not only to reduce emissions, but mainly to move away from fossil carbon by substituting fossil feedstock with renewable carbon [CO2, 2024] [MER, 2023] [GCI, 2022] by creating a circular carbon economy.

However, several peer-reviewed scientific studies have shown the efficiency of CCU applications e.g. by calculating the quantity of CO_2 that could be reused [HEP, 2019] [KOY, 2018] or by performing full Life Cycle Assessment (LCA) on various CCU routes [KAT, 2019] [ARTZ, 2019] [OST, 2020] [DIM, 2020]. LCAs show that depending on the context, the climate mitigation potential of CCU varies.

These technologies can lead to [SAP, 2022] [MER, 2023]:

- Net reduction of CO_2 emissions with respect to conventional pathway (use of fossil feedstock) to produce the same final product, but with renewable carbon feedstock.
- Net zero CO_2 emissions when CO_2 emissions used as feedstock for the production process are stored durably in products (e.g. through mineralisation), or when they are re-emitted at the end-of-life of the product but then recaptured and recycled, or when CO_2 is captured from the atmosphere and returned to it at the product's end-of-life.
- Net CO_2 removal when CO_2, which is captured from the atmosphere or from the treatment of biomass, is durably stored in products via mineralisation processes.

Several studies [IPCC, 2022] [GONG, 2021] [FAR, 2019] [BRE, 2019] show that CCU can reduce CO_2 emissions independently from the duration of CO_2 storage in a product and the long-term goal should be to close the loop (prevent CO_2 to finally reach the atmosphere), move away from fossil fuel and create net-zero emission processes.

Because of its multi-faceted approach and high granularity, CCU technologies have been so far largely neglected in the development of climate and energy models, and as a result its contribution is not visible yet in future energy and climate projections. However, the potential of CCU is now recognized by the climate community and discussed in the last report of the IPCC Assessment

Report (AR6) [IPCC, 2022] as a key opportunity for climate change mitigation, energy transition and a reinvention of the industrial sector, benefiting society as a whole.

4. The role of CCU technologies per sector

4.1. CCU in the transport and energy sectors

To reach net zero emissions from the energy sector, fossil fuel-based energy demand should be mainly replaced by renewable electricity (RE) [RAM, 2020]. 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 [FAR, 2019] [GAL, 2022]. In the long term, net zero emissions could be achieved by "defossilising" the energy and transport sectors, whereby carbon from fossil sources is replaced by direct electrification where possible and for the remaining cases by hydrocarbons that are created synthetically from CO_2 and H_2 produced with low carbon energy, enabling the production of CCU fuels. These fuels can be stored, transported and used as such or to produce electricity again. Liquid CCU fuels (e.g. e-methanol, e-kerosene) are easier (and relatively inexpensive) to store and transport compared to electricity and H_2 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, they can support the indirect balancing of the energy system, and they can bring renewable energy to sectors that cannot use it directly [MER, 2023] [FAR, 2019] [BRE, 2015] [ANW, 2020]. Artz et al., 2019 [ARTZ, 2019] 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 H_2 produced using RE.

Technologies to capture CO_2 from point sources and to convert it into CCU fuels already exist and

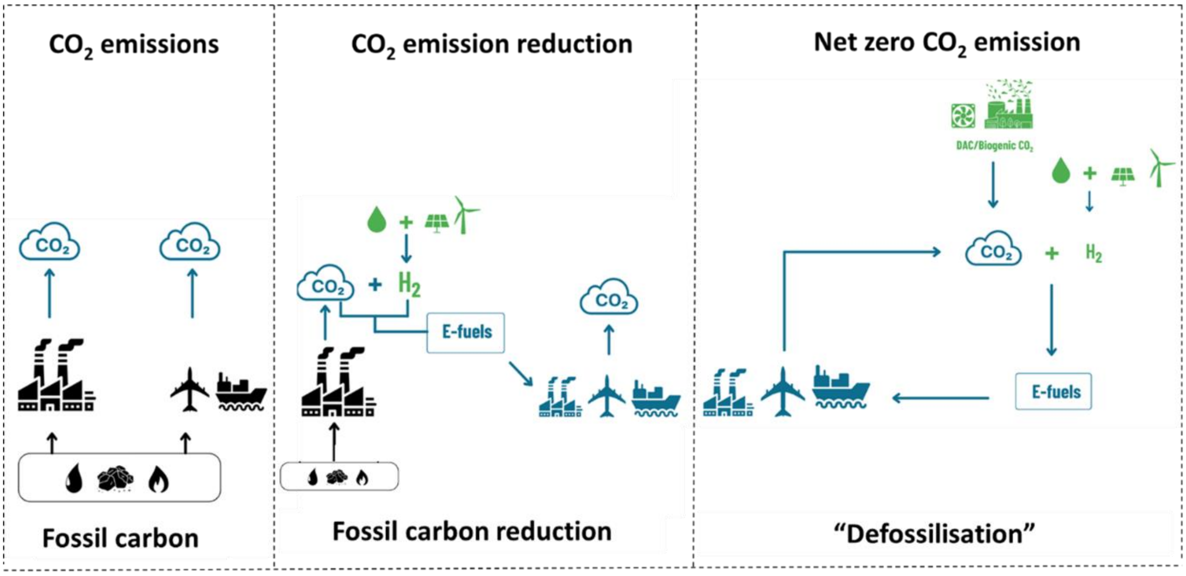

Figure 2: The role of CCU in the energy system (adapted from Mertens et al., Joule, 2023[9]) *[MER, 2023]*

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 [SAP, 2022] [MER, 2023]. Figure 2 shows how CCU fuels can induce CO_2 emission reduction when e.g. industrial CO_2 is converted into fuels and used in the aviation or maritime sectors. Or how CCU can avoid emissions and create net-zero emission processes while CO_2 is captured or at point sources or in the air and it stays in close-loops.

The long-term use of carbon-based energy carriers in a net zero emissions economy relies upon low-cost, scalable, clean hydrogen production for example via the electrolysis of water. The estimated global potential for the scale of CO_2 utilisation in fuels varies widely, from 1 to 6.1 $GtCO_2yr^{-1}$, reflecting uncertainties in potential market penetration [HEP, 2019] [FAR, 2019] [RAM, 2020] [GAL,2022] [GAL, 2022]. 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 [HPEP, 2019] [ANW, 2020] [BYR, 2018].

4.2.CCU in the building industry

The building sector is the most carbon intensive sector of the industry with about 8% of global CO_2 emissions coming from cement production, 75% 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 [GCCA, 2021] 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. The conversion of CO_2, using H_2 produced with RE enables to produce renewable fuels to replace fossil fuels to fire the cement kilns and to bring RE in the process [FAR, 2019], 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 [HILLS, 2020] [OST, 2021] [PAS, 2018].

Mineral wastes such as slags and ashes from the steel and power sectors, respectively, 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 is permanent and nontoxic [NAS, 2019]. Mineralisation enables both gaseous and solid waste to be recycled together (Figure 3).

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 [OST, 2020] [DIM, 2020] [GONG, 2021].

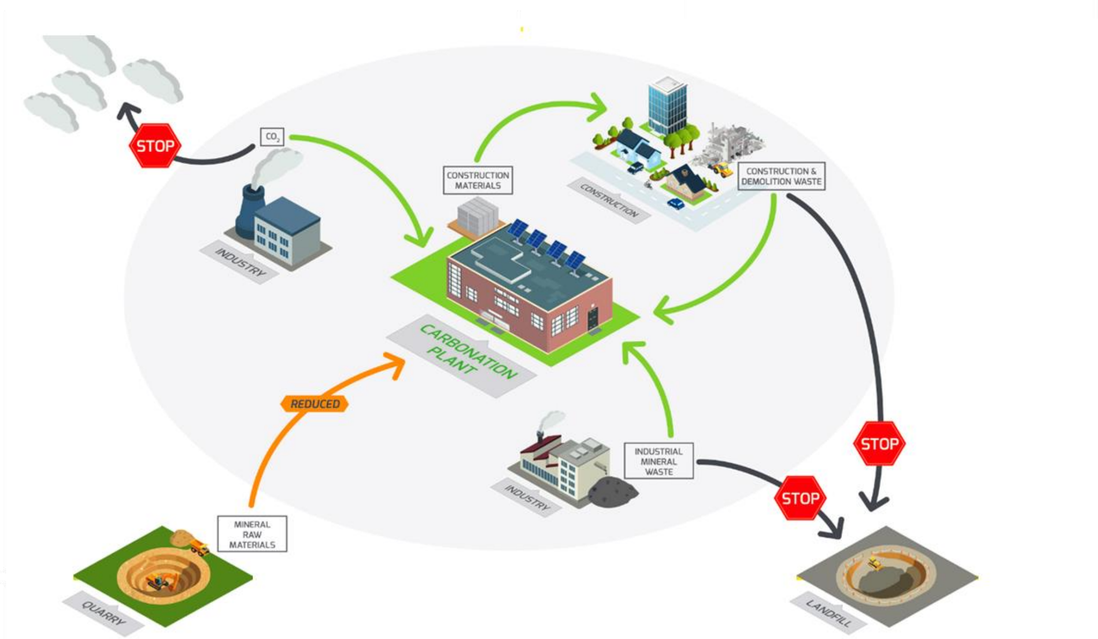

Figure 3: Concept of double circularity for gas and solid waste via CO_2 mineralisation.

4.3.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 [IPCC, 2022] Chapter 11. However, the production of chemicals involves massive use of fossil carbon and significant GHG emissions amongst which about 60 to 70% are embedded emissions [RCI, 2022] [KAT, 2019] [NOVA, 2022]. 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 [RCI, 2022].

CCU via Power-to-X allows bringing RE to the chemical sectors and to use captured carbon as a substitute to fossil carbon [MER, 2023] [GONG, 2021]. Kätelhön et al., 2019 [KAT, 2019] 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 Life Cycle Assessment (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 [HEP, 2019] [IEAGHG, 2019]. 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 [IEAGHG, 2019] 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 [IPCC, 2022] Ch.11 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.

5. How to assess the contribution of CCU technologies ?

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 [BRU, 2016]. 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 [DEK, 2022]. This omits the key role of CCU which is not only to decarbonise emissions, but above all to substitute 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 [BRU, 2016] [NOC, 2020]. 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 [KAT, 2019]. Two important points should be highlighted:

1) If CO_2-based products can be produced with less environmental impact (including GHG emissions, land-use change, water use, …) 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 (are we 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 [GCI, 2022].

6. A quantitative assessment on the contribution of CCU to reach climate neutrality in the EU

6.1. The approach

CO_2 Value Europe (CVE), the non-profit association representing the CCU community in Europe, has launched in January 2024, a first quantitative assessment of the CCU contribution towards climate neutrality in the EU [CO2, 2024]. The association has performed a two-year exercise, together with international experts to assess the mitigating potential of these technologies, by 1) identifying the main driving forces and key uncertainties related to their deployment, 2) developing scenarios that illustrate the role of CCU in the future, 3) creating a CVE Expert Vision based on scenario development learnings, and 4) developing, together with the consultant CLIMACT, an open-access model, the 2050 Pathway Explorer for CCU [CLI, 2024], that yields quantitative information about the role of CCU by 2050 in the EU.

This is the first time that CCU is included in such a holistic climate & energy model and as such, not only the results of the modelling but also the tool itself are important outcomes of this exercise.

6.2. The CVE Expert Vision

The contrasted scenarios were analysed to frame a balanced and scientifically credible CVE expert vision. The objective was to reach the highest values possible in term of GHG emission reduction, amount of CO_2 for utilisation and percentage of CCU product penetration in the market while being mindful of the impact on planetary boundaries including the use of water, land and raw materials, and the amount of energy [MENG, 2023] [BAC, 2023]. Combining information on societal changes and technological levers of the representative CCU pathways, the “CVE Expert Vision” scenario has been modelled using the CLIMACT Pathway Explorer 2050 and the results of this exercise are discussed in section 6.4.

6.3. The 2050 Pathway Explorer for CCU

The 2050 Pathway Explorer for CCU [CLI, 2024] is an open-access web tool able to quantify the climate-mitigating contribution of CCU as part of a more holistic model integrating both technological and behavioural elements. This model is a step-by-step solution enabling the development of energy transition scenarios based on credible and transparent assumptions. In this exercise, the assumptions are mainly based on the CVE Expert Vision scenario 2050 built during the scenario development process.

The model enables to explore possible futures and assess the implications and trade-offs of their choices. Simulations can be performed in real time, offering a direct understanding of the key levers of the low carbon transition. The exploration scope encompasses the energy system and its dynamics, all GHG emissions, and the associated resources and socio-economic impacts.

6.4. The Results

Our model results show that about 21% of the technological effort to reach climate neutrality by 2050 will come from CCU. Indeed, the current measures in place to reduce EU emissions represent only 34% of the total effort required. Those measures must therefore be significantly reinforced by additional actions, including societal changes (30%) and technological development (37%). By 2050, CCU will reduce CO_2 emissions by at least 250Mt (21% of GHG reduction from technologies) (Figure 4).

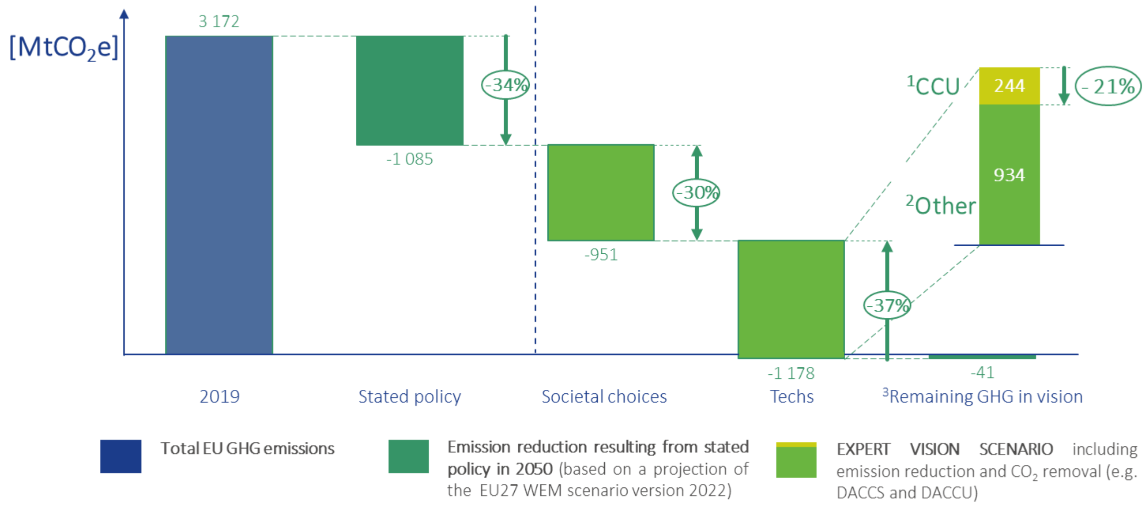

Figure 4: Impact of categories of actions to reduce overall GHG emissions in the EU until 2050 [CO2, 2024]

We show that by 2050, the EU will have the potential to capture at least 320 $MtCO_2$ and that at least half of it will be used as non-fossil carbon feedstock. CO_2 will then be captured from Direct Air Capture (DAC) (26%), process emissions (23%), biogenic emissions (23%), CCU fuel combustion (2%), and from remaining fossil fuel emissions (6%). More than 55% of the captured carbon will be used as feedstock to substitute virgin fossil carbon, while the rest will be stored underground via Carbon Capture and Storage (CCS). From the 173 $MtCO_2$ utilised, 50% will be used to produce CCU fuels, 42% for chemicals production and 8% will be mineralised permanently in building materials.

CCU will play a crucial role "defossilising" industry and transports. By producing 30% of the chemicals, 53% of the fuels, 76% of ceramics, and 100% of prefab concrete (Figure 5), CCU will reduce EU industrial emissions by 20% in 2050. Using CCU fuels in the maritime and aviation sectors will reduce their emissions by 35 and 38%, respectively.

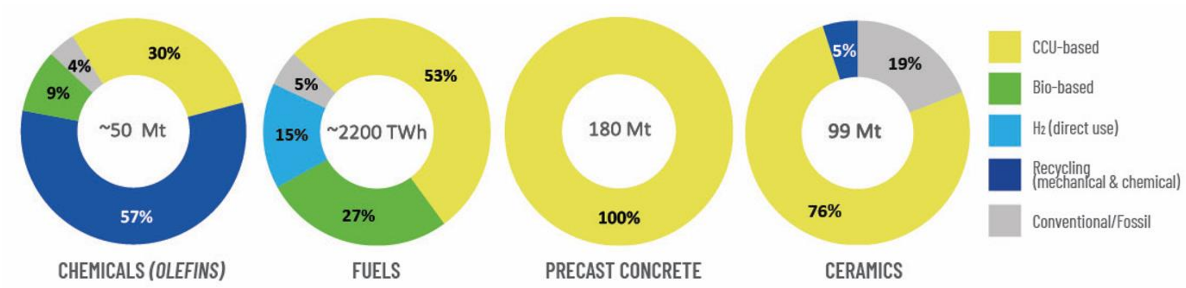

Figure 5: Share of CCU product [CO2, 2024]

CCU fuels are drop-in solutions as they do not require changes in infrastructure. By 2050 about 1161 TWh of CCU fuels will be consumed representing about 17,5% of total final energy consumption in the EU. The main part of these fuels (69%) will be used in the aviation and maritime sectors, while the rest will be used in land transport (21%), mainly heavy vehicle and inland waterways, and in the industry (18%).

The domestic production of these CCU fuels and chemicals for the transport and industry sectors will require up to 1187 TWh of low-carbon electricity in 2050 (including DAC, carbon capture at point sources, production of H_2 and final product generation). This represents approximately 22% of the modelled low-carbon electricity production in the EU by that year and it is one of the main challenges for the upscaling of CCU fuels and chemical production.

As for the mineralisation of CO_2, the process does not require significant amount of energy and it can store CO_2 permanently in building materials. By 2050, at least 14 $MtCO_2$ (10% of the total CO_2 stored) could be channelled in building materials. These numbers are constrained notably by product demand and the availability of wastes and minerals as feedstock for the reaction but could be significantly higher when adding more mineralisation pathways into the model. Moreover, CO_2 mineralisation has the potential to perform Carbon Dioxide Removal (CDR) when the CO_2 sources captured come from Direct Air Capture (DAC) or biogenic sources.

These modelling results are providing quantified answers to a series of questions on the role that CCU can play towards reaching to EU's climate and circularity goals, with a focus on the 2050 carbon neutrality milestone. To fulfil this role and allow CCU to realise its potential, a series of actions are needed to create market incentives and a favourable regulatory framework to allow for the upscaling of CCU. Our full report [CO2, 2024] will bring more information on further recommendations.

7. Future Opportunities and Challenges

The deployment and upscaling of CCU technologies at global scale will play a crucial role to decrease emissions, especially from hard-to-abate sectors, but also to move away from fossil fuels in the transport and chemical industries. CCU technologies are drop-in solutions that have the potential to utilise CO_2 at a few gigaton per year by 2050 globally. They enable significant emission savings for transports 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.

The main opportunities related to CCU technologies are:

- The reduction and avoidance of CO_2 emissions whilst maintaining essential services historically based on fossil resources,
- Their potential to create negative emissions via CDR when atmospheric or biogenic CO_2 is permanently stored in products,
- The production of CCU fuels using renewable energy allowing, among others, for the indirect balancing of the energy system,
- Their potential to bring renewable energy to sector that cannot use it directly
- The "defossilisation" of the chemical, energy and transport sectors,
- The enhancement of circularity and a reduced demand for non-circular raw materials.

The full-scale deployment of CCU may be hindered by:

- 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 strategies,
- The local acceptance of the required technical infrastructure and the market acceptance of CO_2-based products,
- The conflicting expectations on the sociopolitical level regarding CCU and its association or not with CCS.

In conclusion, CCU technologies directly target the cause of climate change via direct utilisation of climate-damaging emissions, but also 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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