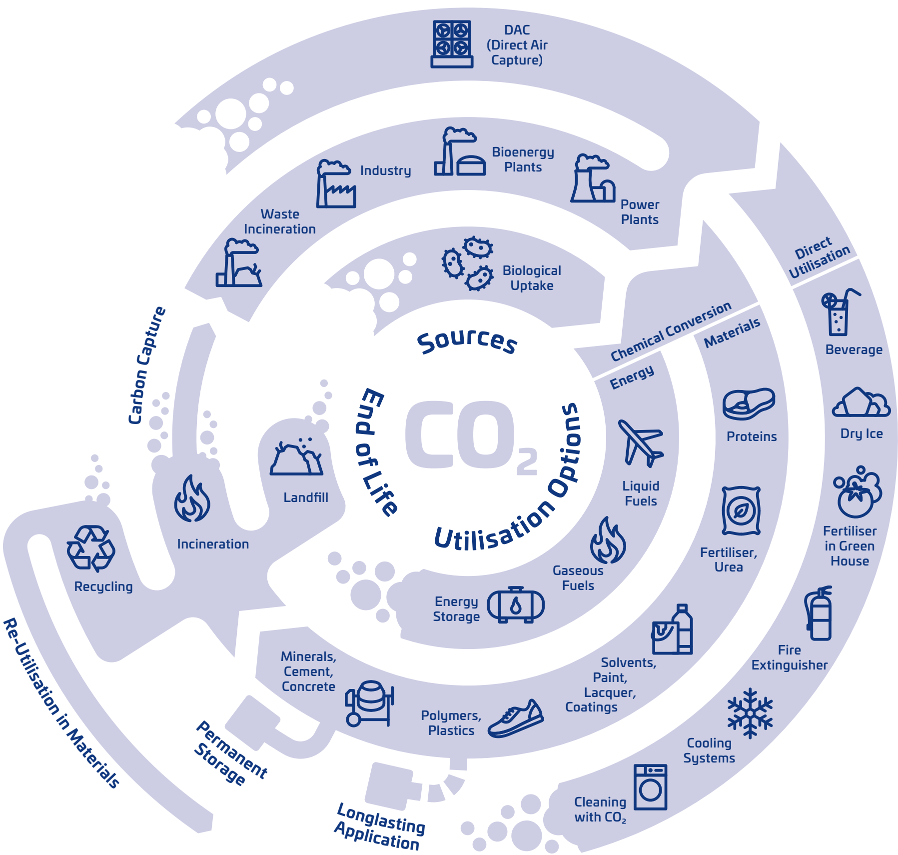
RENEWABLE CARBON INITIATIVE
REPORT

Making a Case for Carbon Capture and Utilisation (CCU)

It Is Much More Than Just a Carbon Removal Technology



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July 2023

Renewable Carbon Initiative (RCI)
www.renewable-carbon-initiative.com

Imprint

How to cite

vom Berg, C. and Carus, M. 2023: Making a Case for Carbon Capture and Utilisation (CCU) – It Is much more than just a Carbon Removal Technology. Renewable Carbon Initiative (ed.), Hürth 2023; (vom Berg & Carus 2023)

Editor

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Glossary

You can find the glossary of RCI at https://renewable-carbon-initiative.com/renewable-carbon/glossary/

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Christopher vom Berg is Executive Manager of the RCI and develops strategic concepts for transforming the chemical and material industry towards renewable carbon. He joined nova-Institute in 2017 and has worked on various projects for the Sustainability department and the Economy & Policy department. In 2020, Christopher helped founding the Renewable Carbon Initiative (RCI), where he took over increasing responsibilities over time. Today, he is mainly involved in the management, advocacy and networking of RCI, investigates policies and regulations that impact renewable carbon management, and shares and discusses its positions and opinions. He is also author and co-author of multiple background reports and position papers of the RCI.

Michael Carus is one of the leading European experts, market researchers and policy advisers of the renewable carbon economy – including bio-based, CO_2-based and recycling. At the end of 1994, he and five other scientists founded the private and independent nova-Institute for Ecology and Innovation. Ever since the beginning, Carus has been involved in the company as owner and one of the two Managing Directors. Today nova-Institute has nearly 50 scientists from a wide range of disciplines, covering markets, technologies, sustainability, communication and policy. In the year 2020, Carus founded the Renewable Carbon Initiative (RCI), which has today more than 50 members from chemical and material industries

Executive Summary

CCU enables the substitution of fossil carbon in sectors where it is necessary, supports the full defossilisation of the chemical and derived material industries, creates a circular economy, reduces the emission gap, promotes sustainable carbon cycles, fosters innovation, generates local value and stimulates job growth.

> *"**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."*
>
> (Sapart et al. 2022)

The central goal of the Renewable Carbon Initiative (RCI) is to facilitate the transition from fossil to renewable carbon in all chemicals and materials. Besides biomass and recycling, carbon capture and utilisation (CCU) is one of the three available options to provide renewable carbon, but its potential is not yet fully recognised by policy makers. One main cause is the widespread misconception that CCU only delays emissions and therefore does not contribute to climate change mitigation or net-zero targets – two critical goals that are at the heart of global climate policy. When policy accepts CCU, it is often in the context of long-term storage of carbon or atmospheric/biogenic carbon dioxide removal.

But CCU is much more than a carbon removal technology. It offers multiple solutions to pressing problems of our modern world and can support several Sustainable Development Goals if implemented properly. A key advantage is that CCU supplies renewable carbon to – and thereby substitutes fossil carbon in – sectors that will require carbon in the long run – including the chemical sectors and products like polymers, plastics, solvents, paints, detergents, cosmetics or pharmaceuticals. But CCU is also essential to a long-term net-zero strategy, crucial for creating a sustainable circular economy, providing solutions for scaling up the renewable energy system, and bringing multiple benefits for innovation and business.

It is important to emphasise that CCU can only provide these benefits when powered with renewable energy. And most CCU processes need large amounts of renewable energy. But the use of renewable energy for CCU is a sensible and responsible application, both in the chemicals and materials sectors as well as in aviation and container shipping. For chemicals and materials, there are no alternatives to using carbon in the molecules, and for aviation and container shipping, there are no viable carbon-free alternatives to power these transport options. Currently, more than 90% of these sectors' carbon demand is supplied by fossil carbon from the ground, which is the main driver of climate change. In future scenarios of a fully renewable energy system, the energy demand of CCU for chemical and material sectors is expected to account for 5%[1] of the total demand, which is lower than these sectors' current share of crude oil demand in comparison.

CCU is a strategic key technology for a sustainable future.

1 5% of the expected energy needs in a 100% renewable energy scenario used for CCU processes for chemicals and materials would be sufficient to cover about 30% of these sectors' carbon demand. The other 70% are covered by recycling and biomass, according to the scenario (see below) (Kähler et al. 2022, Tesla 2023).

Significant benefits and advantages of Carbon Capture and Utilisation (CCU) – at a glance

- **CCU provides renewable carbon as a feedstock that substitutes fossil carbon** in sectors where carbon is an elemental feedstock, while maintaining the goods and services of these sectors.
- **CCU enables the full defossilisation of the chemical and derived material industries** as one of the three options for renewable carbon.
- **CCU reduces the emission gap by providing renewable carbon to different industrial sectors**, where it replaces fossil carbon and related CO_2 emissions in different industrial sectors.
- **CCU critically supports upscaling of renewable energy**, because it enables the storage of surplus energy in mobile energy carriers that are easier to store, transport and distribute than hydrogen, and allow to balance out overproduction and grid destabilisations.
- **Upscaled CCU technologies can already today significantly reduce GHG emissions of fuels, chemicals and materials**, with reductions of 50–90% when compared to established fossil counterparts.
- **CCU is an indispensable component of carbon management** as we need all three renewable carbon feedstocks to cover supply and demand of several industrial sectors.
- **CCU generates value and drives innovation** in many fields as a future industry that enables business cases, economic growth and prosperity.
- **CCU is indispensable to tackle Scope 3 emissions** which include raw materials and feedstock and where CCU carbon uptake principally balances out end-of-life emissions.
- **CCU enables regional self-sufficiency of carbon feedstock**, because renewable energy and carbon from industrial point sources or the atmosphere can be found/deployed anywhere on the globe.
- **CCU enables the Circular Economy and Sustainable Carbon Cycles** by facilitating the circularity of carbon and keeping carbon in a potentially continuous loop.
- **CCU enables a system where the future technosphere can act as long-term storage.**
- **CCU can function as carbon dioxide removal** when it utilises atmospheric or biogenic carbon and stores this carbon long-term in durable products, and even in short-lived products once the future technosphere acts as a long-term storage.
- **CCU can be implemented immediately without the need for major infrastructure investments.** For many CCU applications, all that is needed is a local infrastructure for CO_2 and access to renewable hydrogen networks. Most of the heavy CO_2 emitters meet significant local carbon demand.
- **Implementing renewables and CCU is faster, cheaper and more environmentally friendly than offsetting emissions with CCS.**

CCU is a central pillar for the biggest transformation of the chemical and material industry since the industrial revolution – to decouple the petrochemical industry from fossil carbon, by using renewable carbon. CCU is a crucial technology for the future, as it enables the substitution of fossil carbon in sectors where carbon will be needed long-term and supports the full defossilisation of the chemical and derived material industries. By creating a circular carbon economy, CCU reduces the emission gap and promotes sustainable carbon cycles. Moreover, CCU fosters innovation, generates local value, and stimulates job growth. The consequence of not embracing CCU will be prolonged dependence on fossil feedstock.

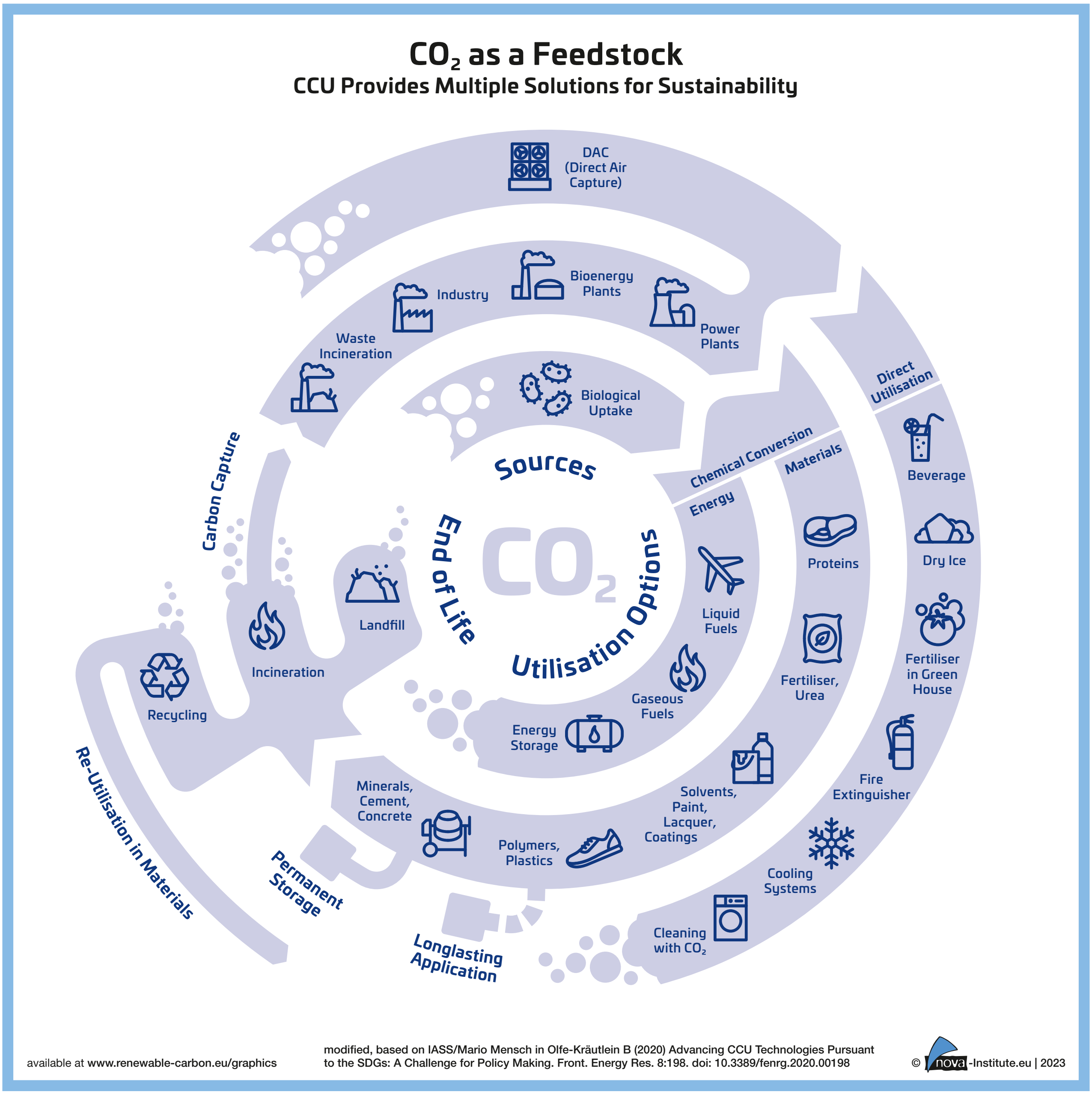

Figure 1: CO_2 as a Feedstock – CCU Provides Multiple Solutions for Sustainability

Why is there only limited adoption of CCU as of yet?

CCU is a young and energy-intensive industry with only a few clear advocates. The technology competes with well-established, upscaled industries that have powerful lobbies (e.g. fossil industries, biofuels sector), across multiple products and sectors. And the strong net-zero focus in policy leads some stakeholders to disregard the remaining future demand for carbon as a feedstock – and therefore to push only for zero-carbon energy and carbon storage of remaining emissions.

Harmonised regulatory support is lacking when it comes to CCU. Instead, a patchwork of regulatory incentives and barriers are in place. This patchwork currently encourages CCU for fuels and for long-term storage, but not for the only sector that has a clear long-term need for carbon supply – chemicals and materials. At the same time, CCU as a recent technology lacks clear advocacy and struggles to gain a foothold under competition to strong, long-established sectors. In order to support the development of the entire carbon capture sector and to enable the development of CCU into a central pillar of carbon management, proper endorsement and support by policy will be necessary.

RCI promotes the following policy measures to enable CCU

- **Aim for decarbonisation AND defossilisation** of all industrial sectors that require carbon as a feedstock, such as the chemicals and materials sector, which has a persistent and increasing demand for embedded carbon.
- **Prioritise reduction of the emissions gap** by reducing emissions as much as possible instead of removing the emissions afterwards.
- **Endorse CCU as a key technology for a sustainable future economy** that needs to be developed and scaled.
- **Develop a clear vision and strategy for CCU** as a key technology for renewable carbon supply in the future.
- **Develop clear and realistic targets for upscaling CCU**, similar to the existing hydrogen or CCS targets.
- **Facilitate a heavy build-up of renewable energy** as an essential prerequisite for scaling up the CCU sector.
- **Establish an enabling framework for industry to build up and access their own renewable energy capacities for CCU at fair conditions**.
- **Positively recognise the substitution of fossil carbon via CCU**, in particular because independence from fossil feedstocks and defossilisation are key targets.
- **Create demand for CCU to facilitate competitiveness** and build-up of an industry through measures such as quotas, multipliers, investment incentives or others.
- **Include CCU- and renewable carbon-based chemicals and materials positively in upcoming product-related legislation** to create a forward-looking and supportive regulatory framework.
- **Avoid creating artificial barriers on using remaining industrial emissions for CCU.** This includes fossil-based emissions while they still exist.
- **The end game of developing carbon capture should be to enable CCU** (circularity of carbon) **and CDR** (removing carbon from the atmosphere).

It is RCI's belief that Europe's first priority should be to minimise the emission gap (and thus the problem of overshooting carbon emissions) as much as possible, while developing carbon dioxide removals as the technological back-up plan to achieve our climate targets. Failing on these targets is simply not an option and therefore well-established carbon capture technologies need to be developed and scaled. But with strong investment in renewable energies and CCU, the remaining emission gap can be significantly reduced to only the truly unavoidable emissions.

The main focus of carbon capture technologies should be on utilising captured carbon in circular fashion (CCU) and on actual carbon dioxide removal (CDR). Fossil CCS is a necessary wildcard to offset unavoidable emissions where they can be captured. However, heavy investment in fossil CCS infrastructure should be carefully weighed against alternatives that minimize the emissions gap, such as renewable energy and renewable carbon, to set clear priorities and avoid fossil lock-in.

Introduction – Carbon Capture and Utilisation (CCU)

Why CCU has to become an essential part of a sustainable industrial transformation

Capturing carbon is a key technology that can enable humanity to address the carbon surplus in the atmosphere, either by capturing carbon-rich industrial emissions to avoid a further increase in the atmosphere, or by taking carbon out of the atmosphere via direct air capture (DAC) or indirectly via biomass.
All relevant carbon capture technologies can be differentiated between two major options after the carbon has been captured. The carbon can either be stored permanently via Carbon Capture and Storage (**CCS**, to take the carbon out of the cycle) or utilised via Carbon Capture and Utilisation (**CCU**, to keep the carbon in the cycle2). Both can be further distinguished depending on the source of the carbon. There is CCS of fossil point sources, CCS of biogenic point sources (often mainly referred to as Bioenergy with Carbon Capture and Storage – **BECCS**) and CCS of direct air capture (**DACCS**). CCU can be similarly distinguished into capturing fossil point source emissions, capturing biogenic point source emissions and from direct air capture. Here, the utilisation can be further separated between products with a rather short life time (from a climate standpoint) and products with long-term storage, e.g. when their life time is on average at least 50–100 years. Wood serves as a widely accepted example. When it comes to actual carbon dioxide removal (**CDR**), only negative emissions technologies that take carbon out of the atmosphere and store it over climate-relevant durations qualify. These include DACCS, BECCS, but also direct biomass uptake, soil carbon sequestration (SCS) and atmospheric or biogenic CCU with utilisation in products with long-term storage. Sapart et al. 2022 summarise CDR accordingly:

> *"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 when the captured CO_2 stays in a closed loop."*

All of the above options capture carbon, but their main purposes differ:

- Fossil-based CCS reduces emissions and stores them permanently → GHG emission reduction by avoiding fossil emissions from the system
- CCU re-accesses carbon in order to provide it as primary feedstock to the industry → GHG emission reduction coupled with cycling carbon as a feedstock back to the system → reduction of the emission gap and a circular carbon economy
- All CDR technologies capture atmospheric (DAC) / biogenic carbon (BECCS) and store it permanently → Negative GHG emissions by taking carbon out of the system

2 The use of the term CCU generally refers to the utilisation of carbon dioxide (CO_2), but can also include industrial carbon monoxide (CO) sources prior to flaring or other conversions to CO_2 before release to the atmosphere. In the US, CO_2 and CO are grouped together as "carbon oxides" for purposes of Section 45Q CCUS tax credits. In this report, "CO_2 utilisation" is meant to also include other carbon oxides.

This distinction is important in light of climate change mitigation discussions and the net-zero target of 2050. International institutions such as the IPCC (e.g. IPCC 2022) and the IEA (e.g. IEA 2022c) use models to calculate development of GHG emissions by 2050 to better understand the net-zero emissions targets of the Paris Agreement. These scenarios usually include a "**remaining emission gap**" (how many emissions are still occurring and need to be balanced out) or "**overshoot**" (by how much are we missing net-zero in 2050, which needs to be balanced out with carbon removals in the years after). This gap or overshooting is caused on the one hand by entirely unavoidable CO_2 emissions, e.g. from the cement sector. On the other hand, the emissions gap and/or overshoot will be larger, the longer continued utilisation of fossil fuels is maintained. This is of particular relevance to the chemicals and materials sector, where carbon will remain an essential feedstock in the long-term, with growing demand, and where fossil carbon needs to be replaced to avoid adding more and more carbon into our technosphere and atmosphere.

To mitigate climate change and truly achieve net zero by 2050 renewable energies are indispensable to decarbonise the energy sector. To defossilise the chemicals and materials sector – **it cannot be decarbonised** – the only option is to switch from fossil to renewable carbon from biomass, recycling or CCU. Because the amount of fossil carbon that needs to be substituted is substantial, only fully implementing all three available renewable carbon options will stop the further inflow of fossil carbon from the ground, the main cause of human-made climate change.

The stark difference between the main objectives of CCU and CCS is often overlooked because of their similar starting point (and acronyms). Both are highly relevant as green technologies for the future, but when the concepts are thought through to the end, it becomes clear that their strategic objective is quite different. Although CCU and CCS capture carbon, they are two separate concepts, in terms of downstream technologies, in terms of actors and investors, and in terms of impacts on industry. Sapart et al. 2022 state:

> *"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."*

CCU, if applied broadly and comprehensively, and in combination with biomass and recycling to create truly sustainable carbon cycles, would ultimately lead to the complete avoidance of using virgin fossil feedstocks, while at the same time keeping the European economy running on valuable feedstocks. It therefore contributes to the stated top priority of EU climate policy – emission reductions. In contrast, CCS and CDR come into play to manage and compensate for the remaining fossil and entirely unavoidable CO_2 emissions. In the past, CCU was often considered to be limited in volume, but also here scientific evidence has changed the picture: the potential of CCU to replace large volumes of fossil carbon in all sectors that require carbon not for energy, but as a feedstock, is immense and essential for the complete defossilisation of the chemical and material world (e.g. Hepburn et al. 2019).
The EU has stated that removing carbon from the atmosphere is only secondary to reducing overall emissions, but storage and removal of carbon are at the moment treated as priority compared to CCU within the policy context.

The importance of carbon capture and utilisation is comparatively underestimated. To some extent, this is due to the fact that CCU is often compared to CCS based on their potential as a carbon dioxide removal technology. Several publications investigated CCU and CCS technologies in terms of net-zero targets, CDR potential and/or the duration of CO_2 storage, and here, the studies conclude that most CCU technologies

perform poorly when compared to CCS (e.g. de Kleijne et al. 2022 or Mac Dowell et al. 2017). This conclusion can be principally debated because CDR refers to the removal of carbon from the atmosphere – and to achieve this, only atmospheric or biogenic carbon can be used, not fossil carbon. Both CCU (e.g. via mineralisation products) and CCS (via long-term storage) can provide CDR when coupled with atmospheric or biogenic carbon, but at the same time both cannot provide CDR when coupled with fossil carbon.
But **the main purpose of CCU is not carbon dioxide removal**, which is only one facet of the multiple benefits CCU has to offer. Narrowing down the utilisation of carbon to the removal aspect does the technology no justice, because it provides a variety of other solutions.

When assessing CCU, carbon dioxide removal and long-term storage are not the primary environmental benefits, but keeping carbon in a cycle and providing renewable carbon as a feedstock. CDR and long-term storage via CCU are just additional icing on the cake in those products that store carbon over climate-relevant durations.
Olfe-Kräutlein (2020) analysed the potential contribution of CCU as a technology towards the Sustainable Development Goals (SDGs), and concluded that

> *"some SDGs are likely to be supported by the implementation of CCU, whereas others will require specific policy support in order to realize their full potential or to avoid unwanted negative effects".*

In total, the study noted that CCU can provide direct positive contributions to 6 SDGs (see Figure 2) and could have further both indirect positive (9 SDGs) and indirect negative impacts (9 SDGs), which acquire attention and action to realise or mitigate.

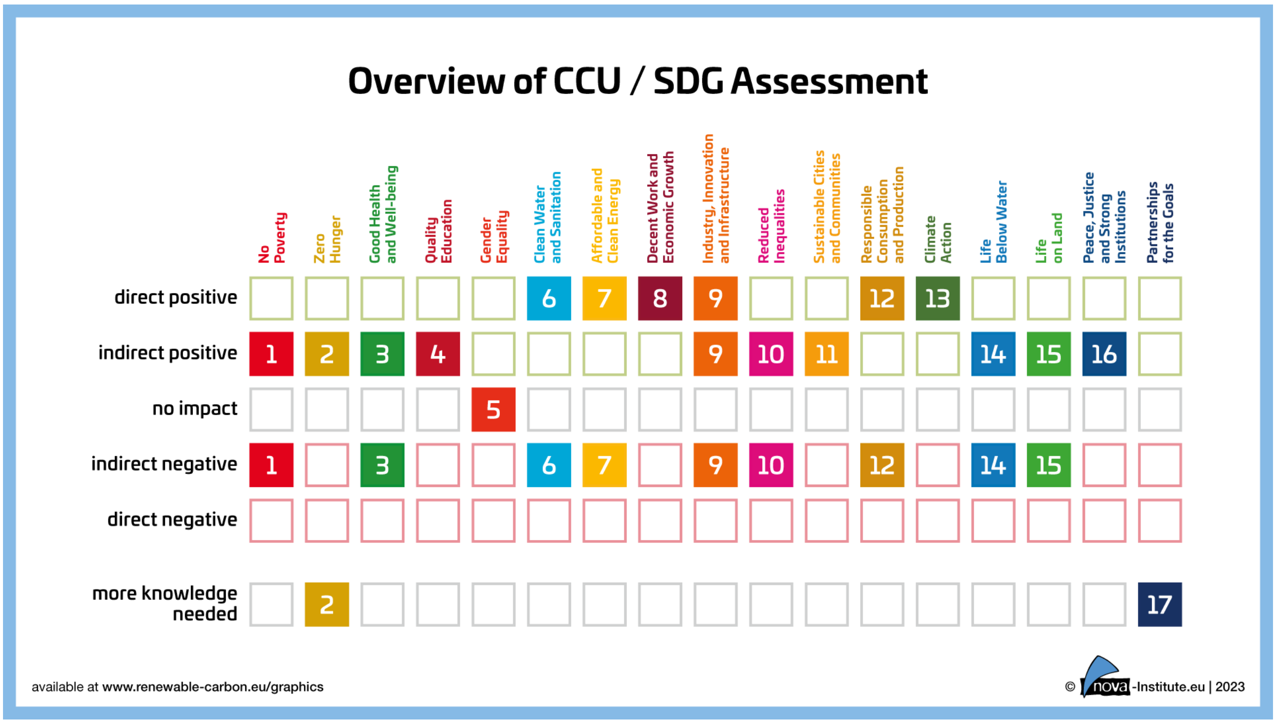

Figure 2: Overview of CCU / SDG assessment (Olfe-Kräutlein 2020).

This position paper undertakes a comprehensive analysis of CCU based on recent scientific publications. The paper thus describes a **holistic picture of CCU as a multiple problem solver and how the implementation could receive the necessary support from policy makers to allow for a successful transition towards sustainability and circularity.**

Carbon capture and utilisation – a deep dive into an essential technology

CCU provides renewable carbon as a feedstock that substitutes fossil carbon

Using fossil resources is the main reason for human-made global warming and the resulting change in our climate. According to recent climate statistics, approximately 70% of all greenhouse gas (GHG) emissions that cause global warming originate from fossil fuels (IPCC 2021). This means that a drastic shift away from fossil fuels is a core element of any strategy seriously aiming to reduce climate change to a minimum and stay within the 1.5° goal of the Paris agreement.

It is important to have a clear understanding of and vision for the future. There will always be demand for carbon as a feedstock, it is the basic building block of life. The **chemical industry** uses fossil carbon not only for process energy (which can be decarbonised) but also as embedded carbon, i.e. the carbon in the molecules. In a future without fossil feedstocks, the still growing demand for embedded carbon needs to be met with renewable alternatives that substitute their fossil counterparts. This embedded carbon cannot be substituted by anything else but the available three renewable carbon sources. These sources are carbon from biomass, recycling and direct CO_2 utilisation. All these sources cycle carbon at different levels. Recycling keeps carbon in the technosphere, bio-based and DAC removes carbon from the atmosphere, and CCU at point sources captures it on route to the atmosphere. All of them are feedstock options that substitute the need for additional fossil carbon from below ground. In light of the urgency of climate action, the more and the sooner fossil carbon is replaced with renewable carbon, the more the remaining emissions gap towards net-zero is reduced (see also the excursus on unavoidable emissions and the emissions gap). This substitution of fossil carbon from the ground is a key argument for CCU because it enables truly sustainable carbon cycles. Unlike fossil carbon (which is essentially linear, as it has been buried underground for millions of years), all three renewable carbon options provide carbon in a circular fashion.

> *"Moreover, the key role of CCU as a crucial vector to move away from fossil fuel dependency needs to be fully recognized."*
>
> (Sapart et al. 2022).

CCU enables the full defossilisation of the chemical and derived material industries

All three renewable carbon sources will need to be developed and utilised for a realistic chance of fully decoupling the entire embedded carbon demand from fossil feedstock. To achieve **defossilisation, CCU is one of the indispensable three pillars** to guarantee the supply of renewable carbon where it is still needed. **Recycling** can realistically keep a total of 50–60% of the carbon in the cycle because unavoidable losses along the entire value chain will limit recycling to a certain upper ceiling. The remaining gap can be closed by carbon from **biomass** and **CCU**, but realistically both options need to be fully endorsed to replace the immense amount of fossil carbon in a sustainable way. Biomass is limited due to land availability, competition with other uses (with food as a priority) and biodiversity issues. Most CCU applications, are heavily dependent on renewable energy, and require quite a lot of green hydrogen to transform the CO_2 and access the carbon molecule. Under the assumption of a growing and by 2050 dominant renewable energy system, CCU will become a (close to) zero emissions technology in the future of the chemical industry, and it is of paramount importance that it gets treated as such when considering future development and the direction of policy and research.

For a careful estimation of the future supply of carbon, RCI developed a scenario in which recycling covers around 55% and biomass covers roughly 20% of the growing carbon demand for chemicals and materials by 2050. The remaining gap of ca. 25% can be covered by CCU technologies in combination with renewable energy – see Figure 2 that visualises this possible scenario for the year 2050 (Kähler et al. 2023). These assumptions are based on the visible policy focus on **recycling** as well as on the limitations of biomass and renewable energy. For the fractions that cannot be recycled mechanically, chemical recycling becomes a key element. Various studies consider a maximum overall recycling rate of 50 to 60% realistic, in some sectors like plastics even 70% may be achieved. However, since the total share also includes difficult to collect groups like detergents and solvents, the overall share is set to 55% in the scenario, which is ambitious in any case. The **biomass** share of 20% is mainly limited by the areas available for cultivated biomass and planted forest, based on the need to preserve biodiversity, which is increasingly becoming a focus of sustainability and policy. About a quarter of the area (that supplies the 20% of biomass) is land previously used for biofuels but now being freed up due to ongoing electrification. The remaining 25% is covered by **direct utilisation of CO_2** (from point sources and direct air capture). This represents only a small share of the possible potential of CO_2 utilisation, but which is heavily dependent on availability of renewable energy.

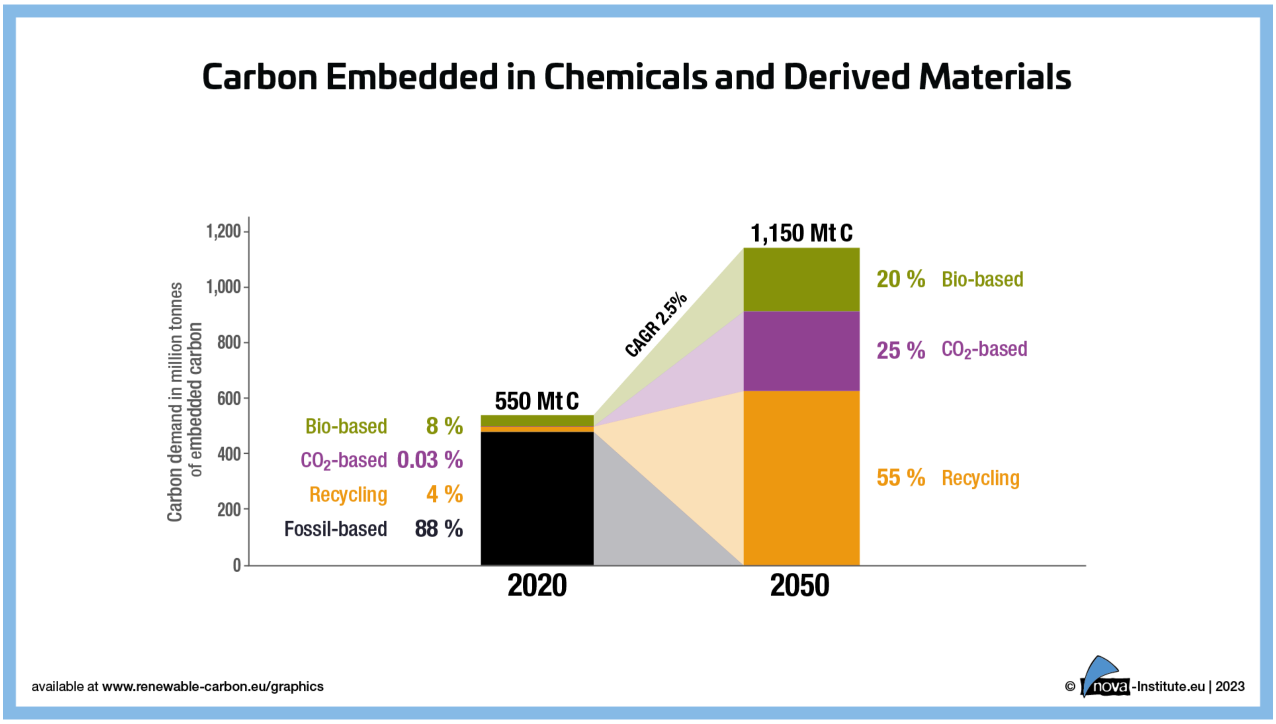

Figure 3: Global carbon demand for chemicals and derived materials in 2020 and scenario for 2050 (Kähler et al. 2023).

A review of recent studies and reports on similar future scenarios for a net-zero chemicals and plastics industry shows that literature in most cases agrees on these assumed shares (Table 1).
The growth rates of feedstock demand for the chemicals or plastics industry in eight of the studies are between 1 and 4% CAGR depending on the scenario, with most scenarios between 2 and 3% CAGR. All studies consider biomass, CO_2 and recycling as possible alternative carbon sources to replace fossil carbon. In some studies, the share of fossil carbon is zero (full defossilisation), in other scenarios high fossil shares remain, often combined with CCS deployment. In most of the scenarios, the **share of biomass is between 20 and 40%** of total demand. The **utilisation of CO_2** is estimated to be slightly lower than the biomass share in the majority of scenarios, and **is projected to be between 10 and 30%** of total demand. The widest range is found for the predicted share of raw materials from recycling, with all studies considering both mechanical and chemical recycling: the total share of **recycling ranges from 10 to 75%**. This means that some scenarios assume that recycling will not take off, while others identify recycling as the main source of raw materials for chemicals and especially polymers. The latter scenarios also estimate high shares for chemical recycling, in some cases even higher than for mechanical recycling.
Despite the different models, assumptions and coverage, the results of the studies are not very far apart and tend to be in general agreement. The largest differences are found within the different scenarios of the individual studies.

Table 1: Ten recent studies on the future of the chemical industry: a deeper look at scenarios on the supply of alternative carbon feedstocks (Source: own research, based on Material Economics 2019, Cefic 2021, Lange 2021, Meys et al. 2021, Bachmann et al. 2022, Ishii et al. 2022, OECD 2022, Orth et al. 2022 and Kähler et al. 2023)

Ten Recent Studies on the Future of Chemical Industry: A Deeper Look at Scenarios on the Supply of Alternative Carbon Feedstocks					
Report	Scope	CAGR: 2–3%	Share Bio-based: 20–40%	Share CO_2-based: 10–30%	Share Recycling: 10–75%
Material Economics 2019	Plastic Sector 2050 (EU)	scenarios show lower demand in 2050 because of efficiency	27–33% (three scenarios); bio-based plus CO_2 "at least 38%"	CO_2 as feedstock is covered, but without separated quantification	25–53%[2] (three scenarios), max. 62%
CEFIC 2021, iC2050	Chemical Industry (cracker) 2050 (EU 27)	high electr.: 2.2% circ.: 1.1% sust. biomass: 2.3% CO_2 capt.: 1.1%	high electr.: 27% (60% fossil) circ.: 17% (54% fossil) sust. biomass: 35% (53% fossil) CO_2 capt.: 1% (88% fossil)	high electr.: 13% (60% fossil) circ.: 29% (54% fossil) sust. biomass: 12% (53% fossil) CO_2 capt.: 11% (88% fossil)	low: 35% (mech. 27%, chem. 8%) medium: 48% (mech. 31%, chem. 17%) high: 65% (mech. 33%, chem. 32%)
Lange, J.-P. 2021 (Shell)	Chemical Industry (cracker & more) 2020-210	a) 4% by 2050, 2% by 2100 b) 4% by 2025, 2% by 2100	40% (1G 10%, 2G 30%)	10%	50% (mech. 15%, chem. 35%)
Meys et al. 2021 (Carbon Minds)	Chemical Industry (cracker) 2050	ca. 4%	21%	33%	45% (20% mech. 25% chem.)
Bachmann et al. 2022	Plastic sector 2030 & 2050	1.2–5.0% (different growth rates per polymer)	5–10% (estimated)	15–20% (estimated)	75% (39% mech., 35% chem.) (optimistic scenario)
Ishii et al./ Systemiq 2022	Chemical Industry (cracker) 2020–2050	3%	up to 43%	up to 45%	up to 3%[1]
OECD 2022	Plastic Sector 2019–2060	2.4%	3%	–	12%
Orth et al. 2022	Orth et al. 2022	4%	90% renewable carbon (authors use the term "zirkuläre Rohstoffe"), 10% fossil carbon		
RCI/nova 2022	Chemical Industry (cracker & more) 2020–2050	2.7%	20%	25%	55%
RCI/nova 2023	Chemical Industry (heavy oil fraction) 2050	2.5%	40% (mainly lignin & pyrolysis oil)	20% (mainly FT)	40% (pyrolysis oil)

1) Recycling is here mainly understood as virgin demand reduction, not as a supply option. 3% are the biogenic part only.

2) Sum is below 100%, because there are also shares for "circular economy in major value chains" and different kinds of stream cracking (with and without CCS).

Most of the scenarios agree that CCU will be indispensable to fully replace fossil carbon. Only through the combination of all three sources, renewable carbon will enable a complete defossilisation of the chemical industry and its diverse downstream products. These products form the basis for almost every industrial sector and almost all consumer goods, and the development of a proper carbon management to satisfy the required demand sustainably.

Today, CCU is mostly used either for enhanced oil recovery and or directly for food, beverages and in greenhouses:

> *"Around 80 Mt CO_2 per year are used for enhanced oil recovery and 30 Mt CO_2 per year for direct use in food and beverage production and yield-boosting in greenhouses."*
>
> (IEA 2022a).

Please note that from RCI's perspective, enhanced oil recovery (EOR) is out of scope for CCU because our goal is to defossilise the global economy and support the shift from fossil to renewable carbon, and not to extract even more fossil feedstock. But also outside of EOR, the use of CCU can grow exponentially in the future:

> *"Plans are underway for around 20 commercial capture facilities (>100 000 Mt CO_2 per year) targeting CO_2 use, mainly in fuels, chemicals and building aggregates. Ten of these projects have been announced since the start of 2021 alone. Around 5 Mt CO_2 per year by 2030 could be captured for synthetic fuels production by 2030, which is almost on track with the 7.5 Mt CO_2 used in synthetic fuel production in 2030 in the Net Zero Scenario."*
>
> (IEA 2022c).

A recent report from Galimova et al. 2022 analysed the global demand for CO_2 as raw material for the production of e-fuels and e-chemicals during a global energy transition to fully renewable energy. This included an evaluation of CCU potentials from key industrial point sources, including cement mills, pulp and paper mills, and waste incinerators:

> *"**the demand for carbon dioxide increases from 0.6 gigatonnes in 2030 to 6.1 gigatonnes in 2050**[3]**.** Key **industrial point sources can potentially supply 2.1 gigatonnes** of carbon dioxide and thus meet the majority of the **demand in the 2030s**. **By 2050**, however, **direct air capture is expected to supply the majority of the demand**, contributing 3.8 gigatonnes of carbon dioxide annually. Sustainable and unavoidable industrial point sources and direct air capture are vital technologies which may help the world to achieve ambitious climate goals."*
>
> (Galimova et al. 2022)

CCU reduces the emission gap by providing renewable carbon to different industrial sectors

The **chemical industry** is the crucial sector when it comes embedded carbon demand, i.e. the carbon in the molecules, because this carbon cannot be replaced.

But also in the **energy sector**, CCU has a role to play. Society will not only focus on green hydrogen, but in many cases take the next step via CCU to go from H_2 plus CO_2 towards syngas, synthetic methane, methanol, ethanol or aviation fuel. **Methanol** in particular is predicted as highly significant in the future, both as a liquid energy carrier and raw material for the chemical industry. In fact, already today significant production capacities of about 150 Mt/y, mainly fossil, methanol exist (IRENA & Methanol Institute 2021). As a liquid energy carrier, methanol is much easier to handle, store and transport than hydrogen. Therefore, the already

3 1 ton of CO_2 contains 0.27 t of embedded carbon. The 0.6 and 6.1 Gt CO_2 emissions translate to a demand of carbon of 0.16 Gt and 1.66 Gt C respectively.

existing infrastructure for transport can be utilised, which makes the defossilisation faster and more cost efficient. Ethanol is another useful liquid energy carrier and can be a building block for multiple chemical applications as well as used as a fuel and a feedstock for sustainable aviation fuel, via the alcohol-to-jet pathway.

In **the aviation sector**, at least for the foreseeable future, **synthetic aviation fuels** from CO_2, CO and green hydrogen are likely the most climate-friendly aircraft fuels. Adding to this fact are recently introduced quotas for sustainable aviation fuels (SAF) and subquotas for synthetic aviation fuels currently being enshrined in EU policies, with EU institutions reaching a deal in April 2023 that demands at least 70% of all aviation fuels being SAF by 2050, of which 35% shall be (possibly CCU-based) synthetic e-fuels ("ReFuelEU Aviation", EC 2021). In the event of biomass shortages, this figure could rise even higher. In any case, SAFs from CO_2 are indispensable to meet the emission targets of the aviation sector and given strong political support, their total volumes could grow to 3 Mt in 2030, rising to 32 Mt in 2050 – equal to 83% of total jet kerosene consumption (Surgenor 2021). The same applies to the demand for sustainable fuels in container ships, which are traditionally powered by heavy fuel oil. CCU-based methanol is an interesting option that already sees growing demand from shipping companies. The necessary modifications to existing diesel engines are minor.

And also in the **construction sector**, a huge potential for CCU exists: Concrete, as one of the dominating construction materials, contributes 5–8% of global CO_2 emissions from the production of cement alone. Changes to **cement and concrete production** and their use can therefore have a profound impact. Two CCU-based options provide potentially climate-neutral options for the future: One is to capture and utilise CO_2 emissions from the cement production process for the production of chemicals and products, and the other is the development of new building materials using the captured CO_2 via mineralisation.

> *"Construction materials such as concrete, aggregates, and wall boards can be made with the use of CO_2. From a climate point of view the lifetime of those materials can be considered permanent. While structures (buildings, roads, etc.) will not last permanently, the mineralized CO_2 in the underlying raw materials will. […] CO_2 utilization between 1.0 and 10.8 gigatons per year is projected with a market valuation reaching 0.8–1 trillion USD/year by 2050."*
>
> (Sick et al. 2022a).

All of these solution help to reduce the remaining emissions gap because they provide, also via entirely innovative and novel pathways, alternatives to the use of fossil feedstock. The less fossil feedstock will be utilised by 2050, the lower the overshoot we have in regards to achieving climate targets, and the smaller remaining emission gap that needs to be tackled via CDR to balance out net-zero emissions.

CCU critically supports upscaling of renewable energy

The rapid expansion of renewable energies, with their fluctuating supply at days and night as well as strong overproduction on windy or sunny days, is a challenge for the grid. A key challenge is to guarantee stable supply of energy when it is needed while at the same time to ensure that surplus energy is used sensibly and without endangering grid stability.

A potential solution comes in the form of **storing surplus energy in transportable energy carriers**. And here, in addition to hydrogen from electrolysis, CCU is of central importance. In combination with CO_2, hydrogen can be converted into methane for natural gas grids and into methanol as a fuel or chemical raw material. The currently planned storage, distribution networks and areas of application for hydrogen can be expanded considerably when coupled with CCU. In comparison to hydrogen, CCU-based energy carriers provide easier storage, easier transport, easier distribution and enable the use of existing infrastructures. Consequently, a mix of H_2 and CCU-based methanol is expected to emerge in the market that allows to overcome existing limitations with hydrogen. In addition, renewable energy can already today be commercially stored in CCU-based intermediates such as methanol (diesel substitute, chemical feedstock), aviation fuels, polymers or soon-to-be-available naphtha (Ruiz et al. 2023).

These energy storage capabilities allow CCU to become a key enabler of a greatly expanded renewable energy system with improved resilience against unused overproduction or grid destabilisation.

> *"e-molecules made from renewable energy will be crucial in the energy transition toward carbon neutrality, in particular for long-term energy storage, long-distance energy transport, and for processes that are hard to electrify in industry or long-distance marine and aviation transportation."*
>
> **(Mertens et al. 2023)**

Van Dael et al. (2022) sum up the role of CCU for renewable energy:

> *"A balanced combination of different CCU strategies is preferable. […] The production of CO_2-based fuels with electrified systems can support the renewable energy transition in an energy storage strategy. […] In the meantime, opportunities arise in the field of energy import, which influences the boundary conditions for CCU: Renewable electricity can be produced in an economic feasible way, at far locations in the world, where solar and wind energy are abundant. In such scenarios, CCU not only serves as a storage strategy for the low-carbon and low-cost energy, but also facilitates its transport towards Europe, in the form of molecules with a high energy density. Indeed, the role of methanol as fuel or platform chemical could then be extended to an 'easy- to-transport' liquid energy carrier."*

Upscaled CCU technologies can already today significantly reduce GHG emissions of fuels, chemicals and materials

Carbon-based products derived from CO_2 can lead to significant carbon footprint reductions compared to fossil-based products from crude oil, natural gas or coal, when they are combined with renewables for process energy. There is solid scientific evidence supported by a rising number of LCA studies which confirm **GHG emission reductions of CCU-based production in the range of 50–90%**. Sapart et al. describe the emission reduction potential of CCU as follows:

> *"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. 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. […] CCU technologies have potential to provide solutions to hard-to-abate sectors and to generate revenues through the production of marketable products. […] 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."*
>
> **(Sapart et al. 2022)**

However, CCU-based products can be already today manufactured with a much lower environmental impact than fossil-based products, regardless of the storage time of CO_2 in the products. Some recent examples are a study from Kaiser et al. (2022) on CCU-based polymers (56–73% reduction), a study by Liebich et al. (2020) on synthetic energy carriers (61 of 62 pathways with relevant GHG reductions in 2050, many with 85–95%) and a study by Müller et al. (2020) on the carbon footprint of the carbon feedstock CO_2 (–0.59 to –0.95 kg CO2eq. per kg feedstock). With the utilisation of biogenic or atmospheric carbon, reductions in GHG emissions of up to 90% are possible; and even with the utilisation of fossil CO_2 from industrial and power plant exhaust gases, savings of up to 50% are still possible. The RCI also released a study that calculated the amount of GHG emissions that could be saved if the entire embedded carbon demand of the chemical industry were covered by CO_2-based methanol in 2050, instead of crude oil, natural gas and coal as is the case today. The total GHG emissions savings would amount to 3.7 Gt/y (Kähler et al. 2022).
Because their carbon is essentially circular, CCU-based products can significantly reduce the emission gap. Or, as Mertens et al. (2023) summarise:

> *"So, if low-carbon energy inputs are used, CCU can reduce or eliminate GHG emissions in absolute terms, which means the statement that CCU is just a delay of the CO_2 emissions is not correct."*

CCU is an indispensable component of carbon management

The demand for embedded carbon is set to rise (see Figure 2). Increasing population, higher incomes and a growing middle class will drive the need for products and thus also for carbon – and this includes already increased material efficiency and changes in personal behaviour. By 2050, estimates suggest that the **embedded carbon demand for inorganic chemicals and derived materials will more than double** (e.g. Kähler et al. 2023). At the same time, for a fully defossilised world, this carbon needs to come from renewable carbon sources only.
Carbon management is needed to properly organise the complex transition from today's fossil carbon from the ground to renewable energy and to renewable carbon across all industrial sectors – in time and volume. Anticipating the current and future demand of carbon is not the only task of a proper carbon management. Sharing, re-using and recycling will play main roles in keeping carbon in a closed loop, in line with the Circular Economy. Mechanical and chemical recycling industries will be largely responsible or innovating their processes to better re-use and recycle carbon. Since keeping the entire carbon in cycle is technologically not possible, additional renewable carbon sources such as biomass and CCU become indispensable. The duty of carbon management is to identify the most efficient and most sustainable pathways of supplying this demand, in which areas, regions, applications and sectors which of the renewable carbon solutions might be the most optimal solution. In this context, CCU is one of the three available pillars and may provide the best solutions e.g. for simple bulk chemicals, where the pathway from CO_2 to final chemical is short, in regions that deal with land or water scarcity or in decentralised, remote locations far away from developed industrial infrastructure. **CCU is therefore a crucial pillar for fully enabling carbon management.**

Proper carbon management also requires harmonisation between the renewable carbon sources – for example, the same sustainability requirements should apply to all renewable carbon streams – biomass, CO_2 and recycling. To make such carbon management a reality requires not only effort from the involved industries, but needs to be structured and directed by policy measures, technology developments and major investments.

CCU generates value and drives innovation

To achieve defossilisation means to decouple the petrochemical industry from petro and to shift towards renewable carbon instead of fossil carbon from the ground. This requires also strong innovation and investments in new technologies.

The entire shift away from fossil feedstock is a tremendous opportunity **to stimulate innovation, establish globally leading future industries, and ensure economic growth and prosperity**. But it will require significant efforts and a technology-open framework for new innovative technologies, processes, intermediates and products. CCU as a technology not only enables this system change, it also accelerates this change because it significantly complements other relevant sectors like the renewable energy and green hydrogen. For example, Mertens et al. 2023 point out that

> *"due to its low volumetric energy density and the challenges related to its storage and transport, using this green hydrogen in combination with CO_2 or N2 and convert it to high-energy-dense molecules (e.g., methane, methanol, ammonia, jet fuel, etc.) will be crucial for long-distance marine and aviation transportation, high-temperature heat in the industry, chemicals, long-distance transport of renewable energy, and long-term energy storage."*

Building up required infrastructure, the option to apply the technology increasingly to biogenic and atmospheric CO_2, fair tax regimes and appropriate pricing of CO_2 emissions in all sectors would significantly boost competitiveness of CCU as a whole and create dynamic opportunities for start-ups and new high-value industries. At the same time, CCU stimulates innovation by creating entirely new processes and products. Thousands of scientists and companies worldwide are developing processes to efficiently convert CO_2 into a variety of products. Figure 1 and 3 indicate how diverse the opportunities of CCU-based chemicals, derived materials and products are already today. These products generate novel business cases, new value chains and a return of investment. The field offers tremendous opportunities for the future of Europe, creating entirely new job fields, requiring novel skillsets and providing the opportunity to create a new, high-value sector in Europe. Focus on a stable framework, investment opportunities and research focus on CCU would therefore stimulate economy and create additional value. A trend that is also increasingly understood by financial experts. A major global investor in renewable energy, hydrogen and CCU said in August 2022: *"With CCU the EU will become stronger, richer, more independent"*.

CCU will be a central and much needed pillar to drive forwards the biggest transformation of the chemical industry since the industrial revolution. The sensible choice seems to be to prioritise closing this remaining emissions gap through further efficiency measures, a focus on a strong expansion of renewables, green hydrogen and support for renewable carbon sources such as CCU. This would create innovation and new business models and support the transformation of the whole economy towards sustainability and a circular economy. This is not to say that CCS and CDR should not be further developed and deployed - they are essential tools to meet our climate goals by 2050 - but that reducing emissions as much as possible should be prioritised over carbon removal to tackle the root of the problem. Sick et al. (2022b) wrote the following conclusion:

> *"CCU has key advantages relative to CCS: it provides a less expensive method to stabilize and even reduce CO_2 concentrations in the atmosphere and oceans; it provides a means to create valuable carbon-based products, and it can be instrumental in fostering a circular carbon economy."*

CO_2-based Products

Nivea Moisturiser
Beiersdorf (DE)

CCU Ethanol
LanzaTech alone will soon have an annual production of 200,000 tonnes in China and Belgium.

Air Eau de Parfum & Air Vodka from CO_2
Air Company (US)

Power to Protein
Avecom (BE)

Zara Dress
Inditex/Zara (ES)

Detergent
dm-drogerie markt (DE)

Potz Cleaning Products
Mibelle (CH)

PET Bottles
Mibelle (CH)

CCU Methanol
Capacities for annual production of 1 million tonnes are already under construction in Australia, Chile, China, Germany, the Netherlands, Sweden and Tunisia.

Wax, Diesel and Naphtha
H&R (DE)

Concrete Block
Carbicrete (CA)

CleanO_2 Soap
CleanO_2 Carbon Capture Technologies (CA)

Fabric
LanzaTech (US) and Lululemon (CA)

CO_2-based Synthetic Fibre
ITA RWTH Aachen University (DE)

Field Hockey Surface Poligras Tokyo GT
Advanced Polymer Technology (AU) and Polytan (DE)

CleanCloud Shoe
LanzaTech (US) and On (CH)

CCU-based Cutlery
Newlight Technologies (US)

CCU Kerosene
Capacities of around 35 million litres annual production are under construction in Norway alone, with several other plants planned to start by 2030, e.g. in France, Canada, Portugal and the Netherlands. If all these projects are to be considered, CCU-based kerosene production could be higher than 150 million litres per year by 2030.

Figure 4: Overview of the diversity of already possible CCU-based chemicals, derived materials and products

CCU is indispensable to tackle Scope 3 emissions

Greenhouse gas emissions of companies are categorized into three "scopes" according to the widely-used and accepted Greenhouse Gas Protocol standards. Scope 1 refers to direct emissions from owned or controlled sources. Scope 2 covers indirect emissions from the generation of purchased energy (electricity, heating, cooling). Scope 3 includes all other indirect emissions that occur in the entire value chain of a company – including emissions from purchasing raw materials and feedstock, from the end-of-life of products, and that also includes the carbon embedded in chemicals, materials and products. Often, claims on climate neutrality by companies are referring only to Scope 1 and Scope 2 (because these are under direct control), but Scope 3 is elemental if we want to truly achieve net-zero emissions. CCU and other renewable carbon sources are therefore critical levers to fully address Scope 3 emissions.

The IEEFA writes:

> *"The 'carbon-neutral' tag has been obtained by using carbon capture to capture the 10–15 percent of Scope 1 and Scope 2 emissions (the emissions generated from producing natural gas) during the gas production process or by purchasing carbon offsets. Yet up to 90 percent of emissions from oil and gas do not occur at production. Instead, these emissions, called Scope 3 emissions, occur when the product is actually used, that is, burnt. As shown in our study, capturing Scope 3 emissions, the biggest chunk of emissions created from using the product, is not being accounted for in these "carbon-neutral" claims."*
>
> (IEEFA 2022)

The embedded carbon in purchased raw materials/feedstock and what exactly happens with this carbon at end-of-life are not always reported (or simply not traceable without huge efforts) in the Scope 3 emissions of a company. Scope 3 reporting is a demanding process that requires coordination along the entire value chain. Currently, it is still an optional reporting category in the GHG Protocol. Chemical and derived material producers often have the majority of their emissions in Scope 3 (60–80%), where then the categories "purchased goods and services" and "end-of-life treatment of sold products" dominate. In those cases, **switching from fossil carbon to renewable carbon is elemental to fully address Scope 3 emissions because then the carbon is in essence circular**. Instead of creating additional fossil-based emissions at end-of-life, there is **a balance between the carbon uptake through the raw material / feedstock and the potential emissions at end-of-life**.

This is not to subtract from the fact that fossil-based emissions from energy use and transport cause the majority of companies emissions. But here, a strong increase of renewable energy and full commitment to net-zero transport technologies pave the way to fully reduce these emissions. This is not possible for the embedded carbon in chemicals and materials. Solutions need to be found to keep this carbon in sustainable cycles, so that not more carbon is released into the atmosphere than is taken out again. And this is exactly what CCU and the renewable carbon concept address. **The switch from fossil to renewable carbon sources like CCU is crucial to properly address Scope 3 emissions of the chemical industry and of all industries using products from the chemical industry.**

CCU enables regional self-sufficiency of carbon feedstock

The idea of a self-sufficient humanity when it comes to carbon as a feedstock has been published already over a century ago in a visionary paper by Ciamician 1912:

> *"On the arid lands there will spring up industrial colonies without smoke and without smokestacks; forests of glass tubes will extend over the plains and glass buildings will rise everywhere; inside of these will take place the photochemical processes that hitherto have been the guarded secret of the plants, but that will have been mastered by human industry which will know how to make them bear even more abundant fruit than nature, for nature is not in a hurry and mankind is. And if in a distant future the supply of coal becomes completely exhausted, civilization will not be checked by that, for life and civilization will continue as long as the sun shines!"*
>
> (Ciamician 1912)

Looking into the future, comprehensive CCU installations can fundamentally change the way humankind deals with carbon-containing raw materials. In every region of the world, there is enough CO_2 available, either from industrial point sources, from waste or certainly from the atmosphere, that can be captured and used. **Via CCU every country of the world can become its own provider of carbon-based raw materials.** This could reduce dependence on fossil (and also bio-based) feedstock providing countries, and the location of related industries will be based rather on the best locations for renewable energies than on trade routes. Countries poor in raw materials might experience entirely new development opportunities.

Additionally, solar-based CCU is – compared to biomass – very efficient from a land use point of view. Solar power utilises the energy from the sun with an efficiency of about 20%, while plants utilise only 1 to 2% of sun light energy via photosynthesis with further losses in the process chain. Compared to bioenergy, some studies conclude that renewable energy provides strong benefits in regards to carbon costs and land utilisation:

> *"[…] if 100 ha of good land were to become theoretically available for climate mitigation, they could generally provide at least as much energy and at least 100 times more carbon mitigation if 1 ha were used for solar and 99 to restore forests" compared to using the 100 ha land for bioenergy.*
>
> (Searchinger et al. 2017).

Renewable energy is highly land-efficient and can, coupled with CCU, be highly capable in removing carbon from the atmosphere to produce fuels and chemicals such as ethanol. From a land-use perspective, CCU can have a yield per hectare that is 40 times higher than plants.

This potential for self-sufficiency in raw materials may have consequences that are hardly predictable. While only a theoretical vision today, extracting raw materials from air anywhere on the globe might become reality in the future.

> *"The access to raw materials is "democratised". In the future, everybody, no matter where they are on the planet, will generally have the opportunity to harvest carbon using renewable energies and CCU technologies and to produce fuels, chemicals or plastics out of it."*
>
> (Carus et al. 2019)

CCU enables Circular Economy and Sustainable Carbon Cycles

CCU supports and supplements the circular economy because it enables to run carbon in controllable cycles either via CCU from point sources or via DAC. For fully sustainable carbon cycles it needs to be considered that even a fully optimised recycling system, also including chemical recycling technologies, will only be able to maintain a certain share of carbon in the material cycles (max. 50 to 70%). There will be always a need for additional "fresh" carbon feedstock in the technosphere, and this carbon can come either from biomass or from CCU and DAC. **Without CCU there will be no sustainable carbon cycles.**

This understanding is fully aligned with the renewable carbon concept and has been recently put into a concept called "Circular EconomyPLUS" in a paper moderated by PlasticsEurope designed as a recommendation for a German Circular Economy Strategy:

> *"The concept of a Circular EconomyPLUS described below aims for a holistic and sustainable system change. The distinguishing characteristic of a Circular EconomyPLUS compared with a conventional circular economy is the input into the material cycle of non-fossil carbon on a production basis that is open to all types of technology. Such an input of carbon dioxide (CO_2) and biomass can balance out unavoidable material losses from the cycle that need to be minimised, and in this way can enable a completely closed circular economy. The main aim of the Circular EconomyPLUS for plastics is to get by completely without the use of raw materials and energy from fossil sources – in other words, complete defossilisation."*
>
> (Plastics Europe 2022).

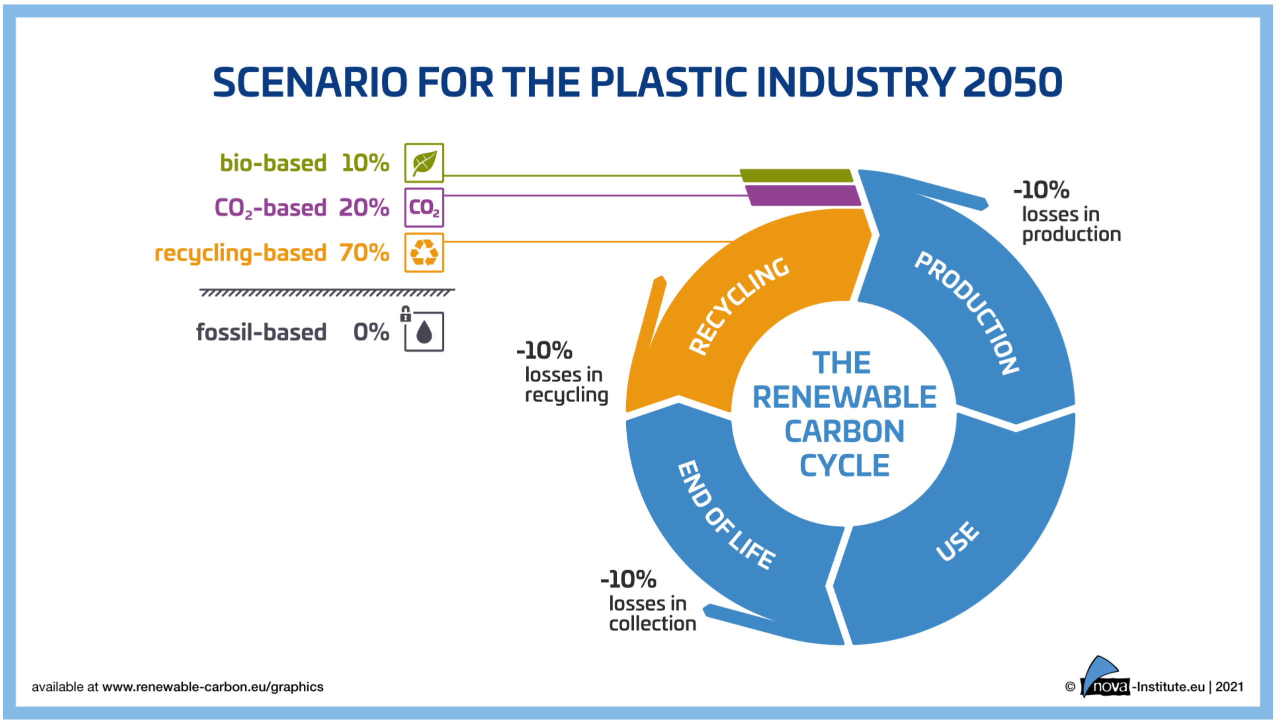

Figure 5: Scenario for a renewable carbon-based plastics sector in 2050 that shows the need of additional non-fossil carbon feedstock besides recycling. This carbon can only come from biomass or CO_2 utilisation

CCU is essential for the sustainable supply of renewable carbon to industry, particularly for all organic chemistry products, including polymers, plastics, paints, detergents, cosmetics and pharmaceuticals. Here, it can maintain a potentially continuous carbon loop in situations where mechanical or chemical recycling is not feasible, but incineration with CCU is. It is therefore vital for a long-term net-zero strategy towards a sustainable circular economy and provides significant benefits to society and environment.

> *"If the plastics industry achieves a 75% recycling rate with advanced recycling technologies in 2030, plastics can comply with their assigned share of the SOS and be considered absolute environmentally sustainable regarding the considered eight planetary boundaries. The remaining virgin plastic production would predominantly rely on CO_2 and renewable electricity from wind, hydro or nuclear power. A smaller portion of plastics would come from biomass."*
>
> (Bachmann et al. 2022)

This is in stark contrast to the storage of carbon, which is a linear end-of-pipe technology that makes it comparatively easy to mitigate fossil-based or any greenhouse gas emissions from large industrial sites. Unlike CCU, CCS does not add value, but removes carbon from the cycle at a cost. With atmospheric or biogenic carbon, CCS can provide carbon dioxide removal, but care should be taken to avoid the risk of fossil lock-in and the associated public backlash that could threaten all carbon capture. CCS could prolong the use of fossil fuels and lead to fossil-linear end-of-pipe thinking. Heavy investment in fossil-based CCS may therefore slow down true zero emission innovation and the transition away from fossil carbon.

CCU enables a system where the future technosphere will act as long-term carbon storage

As the proportion of recycled materials increases in the future, the long-term carbon storage effect of captured carbon and derived CCU-based products will become even more significant, independent of the storage duration. In a strong circular economy, the technosphere will increasingly become a system where the same carbon atom is recycled many times, increasing the number of times the carbon remains in the technosphere. In essence, the **technosphere will become an increasingly stable carbon pool** similar to the e.g. existing carbon pools such as forests. Recycling rates of 70 to 90% for wood, paper, concrete and plastics will be possible in the future – for example, using all available collection, separation and chemical recycling technologies to maximise recycling. If the remaining gaps in carbon demand are met by the alternative renewable carbon options of bio-based and CCU, any additional carbon is essentially circular and does not increase the size of the total carbon pool above ground.

And even the (significantly lower) **losses can be brought back** into the technosphere **via CCU** of CO_2 emissions from waste incineration plants or from the atmosphere via DAC. The combined amount of carbon stored in the technosphere would remain comparatively constant and could act as a reliable carbon storage option, in particular in a defossilised system where no additional fossil carbon is added. In such a future circular economy, CCU could play a similar role to CCS in terms of storage – but instead of permanently removing the carbon from our useful system it is stored in our everyday products.

> *"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."*
>
> (Sapart et al. 2022)

Carbon in the technosphere can ultimately be considered as part of the global carbon stock. This usually refers to carbon in nature, which is defined, for example, as:

> *"The total amount of carbon stored on a plot of land at any given time in one or more of the following carbon pools: biomass (above and below ground), dead organic matter (dead wood and litter), and soil organic matter."*
>
> (IPCC 2006).

However, whether the carbon is stored in biomass or in the technosphere, both in the end form a collective carbon pool that may fluctuate, but is principally measurable and stable.

The argument often used against CCU is that it has no sequestration effect, i.e. that captured emissions are only delayed and quickly returned to the atmosphere, e.g. when used as fuel or packaging. It is true, of course, that products with a short lifetime will not store their embedded carbon for very long. But, if the majority of products are recycled and remaining products end-of-life emissions are captured via CCU to create new products, the carbon is kept several / multiple times in the cycle. The length of storage in a product would become less important in terms of climate change impact. For example, if a product with a life-time of 5 years is recycled / recaptured 20 times, the carbon of the product would also stay in the technosphere for climate-relevant durations. **The future technosphere can therefore act as long-term carbon storage** and CCU is a key technology to facilitate this development.

CCU can function as carbon dioxide removal

Despite all other arguments already mentioned, **CCU can also serve as a CDR technology** under the right circumstances. Actual CO_2 removals via CCU are generated when atmospheric or biogenic CO_2 is durably stored in products. There are a number of durable products that last long-term, i.e. for climate-relevant time periods of at least decades or centuries. Main applications are for example found in construction materials. Wooden construction elements are an accepted carbon storage option when they have life times of 50–100. Similarly, there are different plastic products in modern buildings, which have similar life times – examples are water supply and sewage pipes, heating elements, electricity cabling and insulations, and others. Finally, recycled or CCU-based concrete also fulfil such roles in regards to carbon storage.

If the atmospheric or biogenic carbon is sequestered for the long term, a combination of negative emissions and a building block for a post-fossil feedstock supply is achieved in terms of a future carbon management strategy. In this way, CDR via CCU with long-term storage of the products creates strong synergies towards a more sustainable future.

Excursus – Unavoidable emissions and the remaining emissions gap:

CCS and Carbon Dioxide Removal (CDR) are linked to the concept of the emissions gap, with the idea that these technologies can help to mitigate or offset remaining emissions to achieve net-zero targets. The emissions gap is linked to the idea of "unavoidable emissions". This term describes emissions from sectors or activities for which there is no feasible phase-out option, meaning that these emissions will remain and need to be managed in the long-term.

But what is truly unavoidable is not well defined, and future net-zero scenarios often include large amounts of emissions that are not strictly unavoidable. Galimova et. al (2022) for example write: *"Key industrial point sources of CO_2 considered are the ones that are sustainable and unavoidable due to a lack of alternative technologies. These include limestone fraction of CO_2 emissions from cement mills, bio-CO_2 emissions from pulp and paper mills, and CO_2 from waste incinerators",* indicating only a handful of sectors where CO_2 emissions may be truly unavoidable. And even for today's cement production, there may be alternatives in process and ingredients, and substitutions, for example through wood construction.

For example, according to the IEA's Net Zero Emissions scenario (IEA 2022c), 61% of total energy demand for chemical production will still be met by fossil fuels in 2050:

"Chemicals production: In the NZE, emissions from the chemicals sub-sector fall from 1.3 Gt in 2020 to 1.2 Gt in 2030 and around 65 Mt in 2050. The share of fossil fuels in total energy use falls from 83% in 2020 (mostly oil and natural gas), to 76% in 2030 and 61% in 2050. Oil remains the largest fuel used in primary chemicals production by 2050 in the NZE, along with smaller quantities of gas and coal."

In the IEA's net-zero emission scenario, 7.6 Gt of annual CO_2 emissions are estimated to remain that are balanced via CCUS and CDR. Of this, 5.3 Gt CO_2 are from fossil fuels and processes, 1.4 Gt CO_2 from bioenergy processes and 1 Gt CO_2 from DAC. Out of the 2.4 Gt biogenic/atmospheric carbon, 1.9 Gt CO_2 emissions are permanently stored to balance out remaining, unabated emissions and achieve net-zero. This number might be closer to truly unavoidable emissions by 2050.

The (certainly not unavoidable) fossil fuels that remain in this scenario are used for the production of non-energy goods, where the carbon is embedded in the product (chemicals and plastics), in plants with carbon capture, utilization and storage, and in sectors where low-emission technology options are scarce (IEA 2022b).

However, with a thorough understanding of existing innovative technologies and new projects under development, such as electrically driven crackers (the first of which are available today), chemical recycling, bio-naphtha and CCU-based naphtha, the chemical industry's need for fossil feedstocks can be reduced entirely. There is no scientific reason why the fossil demand of the chemical industry could not be completely replaced by renewable energies and renewable feedstock alternatives.

The IPCC establishes different modelled pathways towards achieving climate targets (of either 1.5°C or 2°C global warming). In the majority of these scenarios, *"a considerable amount of CCS is applied"*. Among the 97 assessed pathways that keep global warming to below 1.5ºC with 'no or limited overshoot' there is a median average of 665 Gt of CO_2 cumulatively captured and stored between now and 2100. Volumes for CDR technologies are estimated at 2.75 (0.52–9.45) Gt CO_2 per year for BECCS, 2.98 (0.23–6.38) Gt CO_2 per year for the removal from agriculture, forestry and land use, and 0.02 (0–1.74) Gt CO_2 per year for DACCS in 2050 (IPCC 2022). In total, the modelled ranges for CDR in the scenarios that achieve low GHG targets are between 0.75 to 17.57 Gt CO_2 per year in 2050, which aligns with the remaining emission gap that need to be balanced out to achieve net-zero. At the same time, the IPCC states that *"the implementation of CCS currently faces technological, economic, institutional, ecological environmental and socio-cultural barriers."*

The projected remaining emissions gap or at least the predicted remaining emissions in 2050 appear in fact largely avoidable if renewable carbon options and renewable energy production were scaled up accordingly and in time. This would in turn also reduce the need for carbon dioxide sequestration to achieve net-zero, and lower the dependency on CDR technologies.

"Relying on untested carbon dioxide removal mechanisms to achieve the Paris targets when we have the technologies to transition away from fossil fuels today is plain wrong and foolhardy." (Watson 2021)

CCU can be implemented immediately without the need for major infrastructure investments

In contrast to CCS, CCU requires a much smaller build-up of new infrastructure. CCS requires a huge network of pipelines and intermediate storage facilities to transport the CO_2 from where it is captured over hundreds of kilometres – from intermediate storage, liquefaction plants or ports to final storage sites, for example in the North Sea in Norway.

CCU, on the other hand, can be implemented in a much more decentralised way. It requires local infrastructure for CO_2 capture und utilisation at industrial sites, combined with access to renewable hydrogen networks, which are already being significantly expanded, even if challenges currently remain. The main sources of industrial emissions are power plants, cement plants, chemical and industrial parks, large-scale industrial biogenic fermentation plants and the wood industry (wood energy, pulp and paper). Most of these emitters meet significant local carbon demand, which is currently supplied by oil and natural gas. CCU could close carbon cycles of emission and demand directly on site. When emissions from one industrial process are repurposed as raw materials for others, sustainable carbon cycles can be created locally with significantly less capital and at a much faster pace. With the implementation of the right policy framework, significant investment in multifaceted CCU solutions could quickly follow.

*"**CCU allows leveraging of existing infrastructure, making the energy transition less disruptive.** As discussed before, hydrogen is challenging to transport and store and requires new infrastructure to be built, implying lots of capital expenditure as well as social acceptance issue. […] However, for 100% hydrogen or for long-distance transport or long-term storage, other molecules such as ammonia, methanol, methane, and kerosene jet fuel are much more suited and, additionally, infrastructure today is in place and could be used to transport, store, and use these e-fuels without any modifications. Given the high costs related to new infrastructure and the social opposition that usually comes along with it, one could think about continuing to use oil and gas pipelines but also LNG terminals and tankers to transport e-methane over long distances or oil tankers to transport liquid e-fuels."*

(Mertens et al. 2023)

Implementing renewables and CCU is faster, cheaper and more environmentally friendly than offsetting emissions with CCS

Investment in renewables should be a key priority because it reduced GHG emissions. This should be of higher importance than removing and storing the CO_2 afterwards. With limited funds available, priority for funding should therefore be given to abatement options that reduce the remaining emissions gap. Several studies confirm that investment priority should be given to renewables (and CCU if carbon is needed) to reduce CO_2 emissions faster, cheaper and more environmentally friendly than maintaining (or even expanding) fossil resources combined with CCS. Recent calculations show that investment in renewables would be cheaper than investment in CCS in most locations: The Energy Transition Commission (ETC 2022) states that *"There is potential for CO_2 capture costs to decline, but at a slower rate than expected for renewables."*, and Tom Evans at independent climate change think tank E3G highlights that renewables are highly competitive:

> *" 'We've seen a dramatic reduction in the cost of clean technology, and those costs are continuing to come down. Renewables are now by far the cheapest energy source almost everywhere.' Wind and solar now account for 75 per cent of global electricity capacity growth, up from 20 per cent in 2008. That is still not nearly enough – we need low-carbon energy sources to be displacing fossil fuels, leading to declining fossil fuel use even as global energy consumption rises. But that turning point is getting closer. 'The economics of renewables is incredibly competitive and will continue to be so', says Evans."*
>
> (Le Page 2022)

The IPCC also draws the conclusion that renewable energy has a much higher mitigation potential at a lower cost than CCS, shown unambiguously by the following image of the latest assessment report:

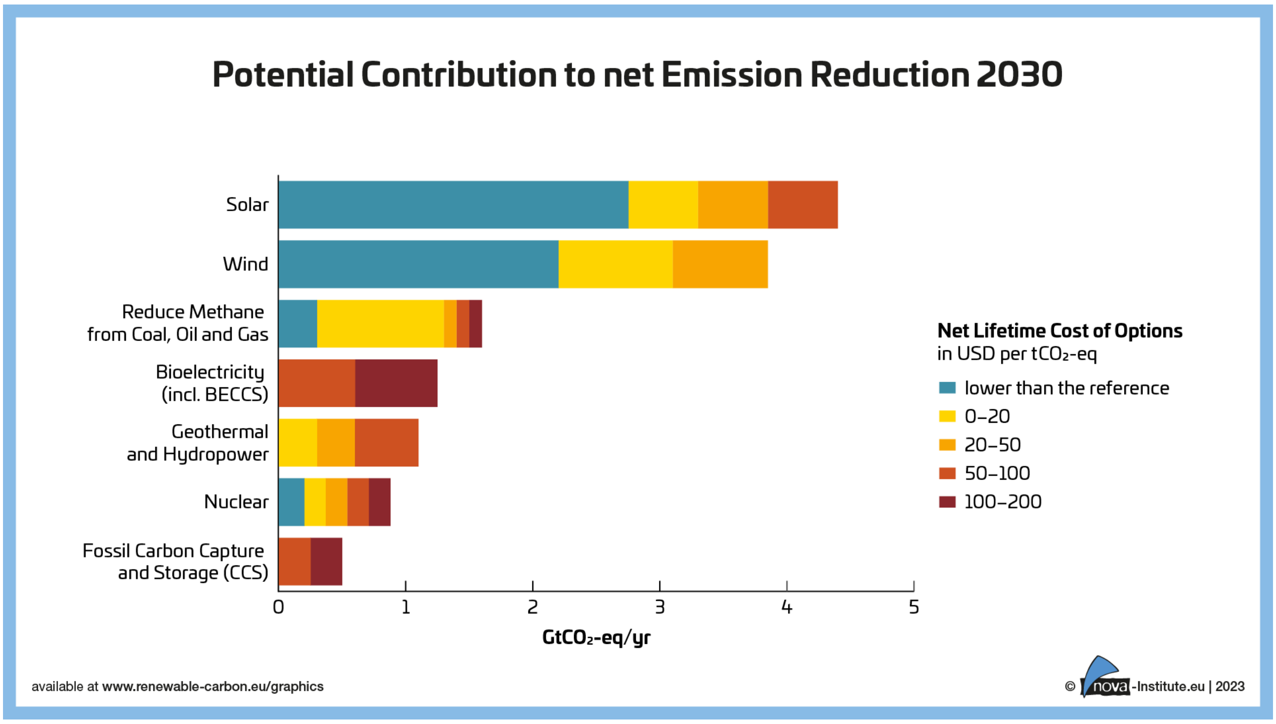

Figure 6: Solar and wind are the cheapest and most impactful mitigation options in the energy sector (based on IPCC 2022)

Renewables are not only cheaper than CCS, they are also the more climate-friendly solution. A recent paper by Aghahosseini et al. 2022 analysed nine global transition pathways for the full decarbonisation of the electricity sector. The results show that fully committing to renewables is more sustainable than the alternatives:

> *"It is explicitly observed from the findings of all the analysed scenarios that a 100% renewable energy system is more efficient and cost competitive than a today's policy scenario relying on fossil and nuclear fuels even by 2050. Entirely renewable scenarios are compatible with the Paris Agreement and the United Nations Sustainable Development Goals."*
>
> **(Aghahosseini et al. 2022)**

It is key to phase out fossil fuels and replace them with direct renewable electricity. However, it is furthermore important to complement this with the production of CCU-based fuels and chemicals based on renewable electricity, which will be needed to defossilise difficult-to-abate segments of transport and industry.

Renewable energy, CCU and biomass

Considerations should also be given to comparing renewable energy and related emission savings with carbon removal via biomass. Solar energy also significantly outperforms storing CO_2 in forests, even in Central Europe. Compared to the current electricity mix in the EU, a ground-mounted PV system saves between 120 (Central Europe) and 170 (Southern Europe) tonnes of CO_2 emissions per year and hectare. In contrast, a forest can only absorb 5 to 11 tonnes of CO_2 per year and hectare, storing only 1.4 to 3 tonnes carbon in the wood.

Additionally, solar hydrogen technology allows for the captured CO_2 to be used to produce chemicals and plastics, which can store significantly more CO_2 than wood materials over the same area and time. By using PV and CCU, 60 tonnes of methanol can be produced from one hectare per year in Central Europe. This green methanol can be used to produce various polymers, and contains 23 tonnes of carbon, equivalent to 84 tonnes of CO_2. As a result, CCU methanol can store more than 10 times the amount of CO_2 as a forest of the same area in Central Europe per year (own calculations, based on Kähler et al. 2022).

Policy support of CCU is growing slowly, but more consistency and ambition is needed

In its recent 6th Assessment Report, the IPCC made clear that carbon capture is a critical strategy in most mitigation pathways and even devoted an entire chapter to CCU and its role in climate change mitigation. This has contributed significantly to putting carbon capture in the policy spotlight. Worldwide, new or revised regulations start to recognise the role of carbon capture and utilisation.

The United States for example have implemented a very strong, supportive policy that financially rewards the use of carbon capture, regardless of the subsequent use or storage of the CO_2. Based on Section 45Q of the US Internal Revenue Code, the CCUS amendment and the Inflation Reduction Act (IRA), the use or storage of carbon from industrial point sources is subsidised at $85/tonne of CO_2 and $180/tonne of CO_2 from direct air capture in commercial production. This is supplemented by a $3.7 billion package of "Bipartisan Infrastructure Law Programs".

These strong clean-tech incentives by recent US regulations prompted a swift response by the EU in the Net-Zero Industry Act (NZIA). The act is aligned with the EUs increased ambitions to reduce GHG emissions, aiming to achieve a 57% reduction (compared to 1990 levels) by 2030 and net-zero by 2050 (EP 2022). But while the NZIA acknowledges CCU as a net-zero technology, it does not name it as one of the strategic net-zero technologies – which makes a difference in terms of the support it can get. Some pockets of EU regulation support CCU, but they fail to offer adequate regulatory incentives for the large-scale economic development of the technology, which is necessary to establish CCU as a significant contributor to future carbon supply and management.

Overview: Regulatory situation in Europe

To highlight the rather fragmented approach to CCU in European policy, a more detailed look at the current regulatory situation in Europe is warranted. Policy makers increasingly understand and embrace the importance of carbon capture, putting carbon capture high on their agenda, providing substantial subsidies, or endorsing them as key technologies. But the treatment of CCU as a technology is highly inconsistent in European policy, and general conclusions and there-of based political recommendations on CCU appear to be often founded on misconceptions (like "no need for carbon in the future") or partial truths.

The following overview provides a summary of key legislation in place or under discussion which impact CCU in Europe. Regulatory support of CCU in Europe is quite fragmented and focused on permanent storage of the captured carbon (highlighted in **orange**), or on the transport sector (highlighted in **blue**), where some long-term need for renewable carbon-based fuels is widely accepted. Other recent key regulations include carbon capture as a means to reduce emissions, but leave out CCU (highlighted in **red**).

- The **Net-Zero Industry Act** as proposed by the Commission, (NZIA, EC 2023a) would include a framework of measures to promote the innovation and scaling up of manufacturing capacity for net-zero technologies. Initially, the proposal listed CCUS as one combined strategic net-zero technology. However, at the last minute, the proposal was revised to include only CCS as a strategic net-zero technology, while CCU was downgraded to a net-zero technology only. Strategic net-zero technologies are eligible for a number regulatory benefits, such as permitting and access to funding – but **CCU is not included**.

- As the first regulatory document based on the Sustainable Carbon Cycles (SCC) Communication, the Commission developed **a Carbon Removal Certification** proposal that was published in November 2022 (EC 2022). The main objective of the CRC proposal is to scale up carbon removal activities and fight greenwashing by enabling companies to demonstrate their actions in this area. This target is important in the context of CCU – the key objective here is not to provide CCU-based carbon as a feedstock for sustainable carbon cycles, but to remove carbon permanently from the atmosphere. In this context, the CRC can help to promote CCU-based technologies, but only those that enable carbon removal through **long-term storage in durable products** (mineralisation, construction materials). The proposal includes "storage of atmospheric or biogenic carbon in durable products or materials" in its definition of a "carbon removal activity", without defining long-lasting as of yet.
- The **Renewable Energy Directive** (RED) includes, as **a sub-target for transport, minimum quotas for e-fuels called Renewable Fuels of Non-Biological Origin (RFNBO)**, and the option to count Recycled Carbon Fuels (RCF) towards the emission reduction targets in transport (EU 2018).
    - **RFNBOs** are fuels produced from forms of renewable energy other than bioenergy. This includes gaseous renewable hydrogen and liquid fuels such as ammonia, methanol or e-fuels when produced from renewable energy. To be counted as RFNBO in the RED, a reduction of greenhouse gas emissions by more than 70% must be demonstrated.
    - **RCF** are liquid/gaseous fuels either produced from (a) liquid or solid waste streams of non-renewable origin or (b) from waste processing gas and exhaust gas of non-renewable origin (non-biogenic CCU of industrial point sources).

  The latest RED revision (RED III) trilogue was concluded in the first quarter of 2023, including a quota for RFNBO shares in transport in 2030. While the final text was not available at the time of writing this report, it appears from press releases that ambitions with regards to synthetic fuels were significantly decreased in the course of the negotiations. While initial proposals by the Commission, Parliament and Council discussed shares between 2.6% and 5.7% for RFNBOs, a (comparatively unambitious) combined transport target of 5.5% for both advanced biofuels and RFNBOs was set. This includes **a sub-quota of 1% for RFNBOs** only. Presumably, a number of reasons led to this final outcome, but it is overall a disappointing outcome for the CCU sector. A potential barrier to the deployment of CCU for fuels is the provision in the second delegated act of the RED II that the use of *"emissions from non-sustainable sources"* (via CCU) to produce RFNBOs and RCFs *"should […] only be considered as avoiding emissions until 2041"* (EC 2023b). In other words, capturing fossil-based emissions to make e-fuels out of them would no longer count as emission reduction.

- For **shipping**, the **Fuel EU Maritime** trilogue concluded and, while the final text still has to be adopted by the EP and the Council, it includes a deal for GHG reductions, a **multiplier for e-fuels / RFNBOs** and a conditional target of 2% in 2034 if RFNBOs amount to less than 1% in fuel mix in 2031 (CVE 2023).
- The EC **ReFuelEU proposal** for **aviation** introduces a mandatory minimum of 28% **synthetic aviation fuels** by 2050 (EC 2021). In April 2023, the EU institutions announced a deal which is supposed to include mandatory shares of SAFs starting at 2% of overall fuel supplied by 2025 and reaching 70% by 2050. It also includes mandatory RFNBOs sub-quotas of 1.2% in 2030 all the way to 35% in 2050 (EP 2023).

- The **Emission Trading System** (ETS, EC 2003a) revision will enable deductions of GHG emissions when **CCU is applied to emissions for mineralisation processes / products that provide long-term storage**, in addition to the already existing deduction for CCS (CVE 2022).
- The ongoing recast of the **Energy Taxation Directive** (ETD, EC 2003b) will set up rules for exemptions for **CCU-based fuels**.
- The **Carbon Border Adjustment Mechanism** (CBAM, latest document European Council 2022) addresses carbon leakage and may incentivise **CCU products with long-term storage** (e.g. for cement).
- The **EU taxonomy for sustainable activities** (EC 2020) also narrows CCU down to climate change mitigation ("increasing the use of environmentally safe carbon capture and utilisation (CCU) and carbon capture and storage (CCS) technologies that deliver a net reduction in greenhouse gas emissions;"). The relevant annex with technical screening criteria for climate change mitigation **does not contain CCU at all**.
- Finally, the **Transition pathway for the chemical industry** (EC 2023c) identifies actions and conditions needed to achieve the green and digital transition in the chemical industry and devotes an entire chapter to feedstocks, one of which is CO_2-based carbon. Recognising the importance of CCU to provide carbon as a feedstock, the document provides hope for increased support for CCU in chemicals and materials in future legislation – however, legal follow-up to the transition pathway is not foreseen as of now.

Despite being the only sector that has a clear long-term need for carbon supply, the chemical and derived materials industry has been largely overlooked in discussions around CCU in Europe. Although the sector is mentioned in communications like the SCC or roadmaps like the Transition Pathway, there are no political incentives for CCU in this industry, primarily due to the misconception that these applications do not help to mitigate climate change or are not net-zero technologies. Unfortunately, CCU is often misunderstood as a bridging technology until industries no longer require carbon, which is a flawed assumption as carbon demand will always exist in certain sectors like the chemical industry. The EU is underestimating the importance of CCU – it should be a strategic key technology for net-zero targets and recognised as such in the NZIA. CCU enables a future circular economy and sustainable carbon cycles, and the many benefits and overall potential of the technology have not yet been fully recognised.

Europe is losing its competitive edge in innovation for CCU

The inconsistent treatment of CCU in European policy leads to regulatory uncertainty and artificial barriers for CCU. Instead of facilitating carbon capture innovation and embracing and developing the economic potential of a key technology for carbon management and the circular economy, the deployment is hampered. European policy instead rather creates artificial (and not necessarily desired) barriers, which create confusion and hinder the development of CCU technologies. The lack of clear and consistent policies on CCU is causing a major roadblock to investment in the technology, leading Europe to lag behind in this field. Many companies have had to abandon planned investments in CCU infrastructure or now resort to complicated and undesirable solutions, such as exporting their captured CO_2 emissions to regions with better incentives for processing into products like methanol or naphtha before importing them back to Europe. A clear and consistent policy framework is urgently needed to create a level playing field and stimulate investment in CCU in Europe. Enforcing defossilisation via technologies like CCU appears to be the correct lever, as it promotes innovation and development of the carbon capture sector, which will be essential for achieving net-zero targets. But it should be implemented in a way that does not inhibit the development and scale-up of such technologies. In particular because a lack of developed carbon capture technologies means that remaining emissions cannot be tackled at point of emission, where they are most concentrated.

Lack of an existing lobby raising awareness for the importance of CCU

Another aspect that should not be overlooked is the lack of an existing lobby advocating for the young CCU industry. The technology competes with well-established, upscaled industries that have powerful lobbies (e.g. fossil industries, biofuels sector), across multiple products and sectors. Additionally, the strong net-zero focus in policy leads some stakeholders to disregard the remaining future demand for carbon as a feedstock – and therefore to push only for zero-carbon energy and carbon storage of remaining emissions.

Even in policy initiatives that originally put a stronger focus on CCU, such as the NZIA or the RED III negotiations, it is visible that the end results are disappointing for the CCU sector. In the first draft of the NZIA, CCUS were jointly listed as a strategic net-zero technology. In the final document, CCU was removed from the list, while CCS remained as the sole carbon capture technology field. The initial RED III revision proposal from the European Commission included RFNBO quotas with a target of 2.6% by 2030, which was confirmed in the trilogue by the Council (albeit likely only meant as indicative, not mandatory target) and an even more ambitious request by the Parliament (5.7%). In stark contrast to these proposals, the final RFNBO quota was set significantly lower at 1%, and instead a combined quota for advanced biodiesel and RFNBO was introduced. This appears to be entirely avoid of ambition from a CCU standpoint, and will likely not be sufficient to make e-fuels competitive. Instead, having to meet only 1% of the total demand is more likely to lead to increased acceptance of higher costs (a premium) for such e-fuels. The point here is not to blame, but instead to highlight that there is no sufficient lobby defending RFNBOs and RCFs or the CCU sector as a whole.

The lack of political advocacy for CCU, coupled with the strong lobby and support for CCS, has convinced fossil fuel producers that investing heavily in building CCS infrastructure is a profitable endeavour. However, this diverts funds away from renewable energy projects and fails to reduce the emissions gap. As a consequence, net-zero strategies will accept a large share of remaining emissions that require equally significant compensations through CCS and CDR, rather than achieving a sustainable, zero-carbon future.

Ways forward for CCU

If the EU were to fully embrace CCU as a key technology of the future, it would lead to increased independence from fossil feedstock, stimulate the transition from fossil to renewable carbon, and establish Europe as a market leader of a highly innovative technology with significant benefits for local value generation and the job market. What would need to happen in order to put CCU in a proper position and pave a pathway for its future development and employment?

There are some basic premises that need to be understood. CCU will **always** require a significant amount of energy to re-access the carbon from CO_2, and this energy needs to be renewable. But if this can be provided, all necessary preconditions are in place. The technological possibilities to deploy CCU exist – first competitive industrial CCU sites in the chemical industry are already up and running. Industries are willing to invest in CCU, and "only" need a competitive framework or enforcing regulation (e.g. via quotas or mandates). And there is a clear long-term need for CCU as a technology that provides renewable carbon as a feedstock – chemicals and derived materials will always require embedded carbon (see Figure 2, Figure 3 and Table 1). The use of renewable energy for CCU is a sensible and responsible application, both in the chemicals and materials sectors as well as in aviation and container shipping. For chemicals and materials, there are no alternatives to using carbon in the molecules, and for aviation and container shipping, there are no viable carbon-free alternatives. Based on these premises, the RCI developed the following policy recommendations that would help to put CCU in a proper position:

Aim for decarbonisation AND defossilisation

Decarbonisation is a complex term – literally, it means to remove carbon, but is usually applied to the avoidance of greenhouse gas emissions. The term drives the notion that there is no need for carbon in the future, but this is a critical misconception. The chemical and material industries, and also transport sectors like aviation and shipping, have a long-term demand for carbon and are essentially only possible with carbon-based feedstocks. Unlike energy, these sectors cannot be "decarbonised", as molecules will always need carbon. The equivalent to decarbonisation via renewable energy in the energy sector is the transition to renewable carbon in the chemical and derived materials industries. Both strategies avoid bringing additional fossil carbon from the ground into the cycle and can be summarised under the term "defossilisation". The final vision is a material sector that covers all its carbon demand by supply from recycling, sustainable biomass and direct CO_2 utilisation both from point source CCU and DAC. **The EU puts strong emphasis on decarbonisation, but needs to also push for defossilisation in the carbon-dependent sectors in order to holistically approach climate change mitigation and achieve net-zero targets.**

Prioritise reducing the emissions gap

In the current political debate, carbon dioxide removal (CDR) has received a lot of attention, not only in the chemicals and materials sector, but also in the energy sector. It is a necessary technology to enable net-zero by 2050, and therefore warrants the development of carbon capture technologies. **But greenhouse gas mitigation should always take precedence over carbon removal. We should avoid emissions first, not focus on capturing or removing them later.** The immense political focus is not only misplaced, it also conflicts with other EU sustainability goals like the circular economy, recycling, the use of non-fossil renewable carbon and the rapid expansion of renewable energy.

Capturing concentrated emissions will always be more efficient than filtering them out of the atmosphere (in a much more diluted state), and as long as fossil emissions remain, there is a need to capture them in order to achieve net-zero by 2050. This minimises the emission gap, which is the most efficient way to defossilise our economic system. A world powered entirely by renewable energy and renewable carbon would require no further fossil carbon. A focus on renewable energies and CCU creates innovation, new business models and support the transformation of the entire economy towards sustainability and a circular economy. This is not to say that CCS and CDR should not be further developed and employed – they are essential tools to achieve our climate targets by 2050 – but instead that reducing emissions as much as possible should be prioritised over capturing in order to tackle the root of issue.

Endorse CCU as a key technology for a sustainable future economy

European policy has so far failed to recognise the importance of CCU – it is much more than just a carbon removal technology. It is essential for a circular economy, for sustainable carbon cycles, it provides significant incentives to innovation and value in building up a future technology sector. The consequence of not embracing CCU will be prolonged utilisation of fossil feedstock because one of the three central pillars for renewable carbon is not upscaled in time.

Europe needs to endorse CCU as a strategically important key technology, that warrants development, support and scale-up. CCU is not automatically sustainable and needs renewable energy, but it is an essential technology for future solutions that enable true sustainability, circularity and achievement of net-zero targets while supplying renewable carbon as a feedstock. There needs to be a shift in mindset away from first demanding proof that CCU is sustainable (there is!) towards an acceptance that CCU is a principally desirable technology that requires political will and support to bloom.

Political recommendations therefore need to extend from fuels and carbon dioxide removal to also include chemicals and materials. It is in particular this sector that will have a demand for carbon as a feedstock in the long-term, and where non-fossil solutions like CCU are of highest relevance.

Develop a clear vision and strategy for CCU

When EU principally recognises that CCU is a strategic key technology, it needs to develop a clear pathway on how it can be advanced and scaled up. RCI recommends the development of a clear vision and strategy for CCU specifically, that puts together the different application sectors, arguments for and against different applications of CCU, identifies development and support needs, clear ideas how to scale CCU up in sectors that need it most. This vision should be placed in the wider context of carbon capture (when to apply CCS, when to apply CCU?) and the EU Green Deal to align with existing legislation.

Part of this vision and strategy should also consider financial support. The EU state aid law prohibits subsidies for commercial operation to ensure fair conditions in EU's internal market, e.g. to avoid that a company from a specific Member State gains an advantage over its competitors. But it is a particular issue that this is exactly what the US are doing for carbon capture, by providing significant subsidies to every ton of carbon captured. To achieve full systemic change, research and pilots are not always enough, and instead a more pro-active intervention in the economy may be required to make desired feedstocks (or more general: outcomes) more accessible without losing competitiveness .

The specific situation in Europe requires further considerations on available options for "structural funding" that might support CCU without the necessity of changing state aid law, jeopardising the internal market or providing large member states with advantages.

Develop clear and realistic targets for upscaling CCU

Similar to what already exists for hydrogen, there have been considerations by industry to propose CCS-relevant targets for 2030 (e.g. minimum storage capacity in North Sea and initial CO_2 grid is developed connecting major hubs), 2040 (e.g. all major industrial sources have access to CO_2 transport and storage, total yearly storage targets, including a biogenic/atmospheric sub-target) and 2050 (higher total storage, higher biogenic / atmospheric sub-target). The first confirmed target has just been laid out by the Commission via the NZIA, which includes a legally binding goal of achieving a yearly injection capacity of a minimum of 50 million tonnes of CO_2 by 2030. **Analogous targets for CCU could be an excellent, complementary action** that would provide market stimulation, allow the build up a CO_2 capture infrastructure for both CCU and CCS. At the same time, CCU would be enabled to provide carbon as a feedstock and CCS would be enabled to remove remaining and unavoidable emissions that endanger net-zero targets.

The visionary 20% target of non-fossil, sustainable carbon for chemicals and plastics by 2030 from the EC Communication on Sustainable Carbon Cycles is a valuable step in the right direction to shift away from fossil feedstock in the chemical industries. But as of now, the goal is non-legally binding, there is no pathway for implementation and it is even unclear what the baseline is and which carbon sources are considered "sustainable non-fossil" sources. RCI argues for an ambitious, binding goal to be formulated in the next few years – at least 20% of renewable carbon sources in chemistry and plastics by 2030, but potentially going beyond by 2035.

Facilitate a heavy build-up of renewable energy

Europe already has ambitious renewable energy targets, with a provisional target of at least 42.5% renewable energy in 2030 and climate neutrality by 2050. The need for renewable energy to achieve net-zero cannot be stressed enough, as it is a prerequisite to sustainably and climate-friendly meet future energy demands and reduce the emissions gap. Defossilisation means to replace all fossil-based feedstock, which is a very dense energy carrier and easily accessible carbon source. Accessing renewable feedstock from CO_2 via CCU (and also from biomass) requires more energy than from fossil feedstock, and this should be properly considered and accounted for.

Prioritising renewable energy and coupling it with CCU also makes economic sense: recent calculations show that investment in renewable energy would be cheaper than investment in CCS in most locations (e.g. Aghahosseini et al. 2022). This is consistent with the findings of, for example, the IEA, which has published a roadmap to net-zero energy by 2050. In this roadmap, The IEA notes that *"There is no need for investment in new fossil fuel supply in our net zero pathway"* (IEA 2022c).

Establish an enabling framework for industry to build up and access their own renewable energy capacities at fair conditions for CCU

European industries have shown a great deal of interest in developing CCU infrastructure on their sites. However, many companies are hesitant due to the high price of renewable electricity in Europe. To support the development of key future technologies, the EU should establish an enabling framework that offers companies competitive opportunities to produce CCU-based chemicals, fuels, and materials. For example, Germany is considering an industrial electricity price, but alternatives such as removing grid charges or specific levies could also be explored if companies invest in low-cost renewable energy – but often, these locations (e.g. wind in the North Sea or PV in Northern Africa) are not located close to the industry. An enabling framework could provide significant momentum to energy-intensive industries in investing in their own renewable energy sources, leading to increased competitiveness and sustainability.

Positively recognise the substitution of fossil carbon via CCU

Similar to how recycling is understood as replacing virgin feedstock, policy should start to positively accept the replacement of virgin fossil feedstock by alternative carbon sources. With CCU, you can – in principle – substitute all carbon from fossil sources (and therefore any additional fossil CO_2 emissions) through the use of renewable energies and CO_2 utilisation. CCU means to leave the already sequestered fossil carbon underground and use carbon instead from above the ground (point sources and atmosphere).

The EU Emission Trading System (EU ETS) could be a potentially strong tool to support utilisation of CCU if the idea of substitution was recognised, since it is also relevant for emissions. In the ETS, credits are granted if emissions are captured and used, but so far only for CCS and for CCU-based mineralisation processes under the revised ETS – a change introduced due to a successful lawsuit by the limestone industry. Many other CCU-based applications are rejected, again based on the understanding that the emissions are not permanently removed. This fails to acknowledge that by substituting fresh fossil feedstock in the subsequent application, the related emissions of this unused feedstock are also avoided. Feasible concepts have been proposed on including CCU in ways that ensure actual emission reductions, for example a study conducted for the German Environmental Agency (UBA), which proposes a set of generally applicable criteria to CCU applications (Dammer et al. 2019).

Create demand for CCU to facilitate competitiveness

For fuels and energy (RED), the EU has found workable solutions that promote renewable feedstocks and ensure their competitiveness through a combination of quotas and a multiplier system. These quotas introduce a clear demand for renewable fuels and renewable energies, around which entire new industrial sectors have been created. The latest quotas for sustainable and synthetic aviation fuels from ReFuelEU and RFNBOs and RCFs from the RED create such a demand for CCU-based fuels. Nothing similar is in place for CCU-based chemicals and materials as of yet – why is there no similar support provided to the only sector that has a clear long-term need for carbon? Creating a stable demand would lead to a clear and reliable market for the industry. There are a multitude of potential levers that could create such demand for CCU, e.g. taxation of fossil carbon; enforcing shares or quotas in chemicals and products, for example through product-related legislation; structures like the European Hydrogen Bank only for CCU; certificates on the renewable carbon content; supportive tax incentives; utilising public procurement or even subsidies for commercialisation.

Include CCU- and renewable carbon-based chemicals and materials in upcoming product-related legislation

The EU is currently still hesitant to add CCU-based chemicals, plastics and other materials into concrete legislation. But in combination with sustainability criteria as a safeguard, CCU-based products could already today be added to manyfold regulations that might provide a critical push for the technology. Example where CCU-based products might be included are the Sustainable Products Initiative, the Packaging and Packaging Waste Regulation (PPWR), the Safe and Sustainable by Design (SSbD) principles or the Chemicals Strategy for Sustainability. Opening up the PPWR to enable CCU-based feedstock in the recycled content quota, or as an individual sub-quota, is highly feasible for drop-in chemicals (i.e. non-fossil versions of existing petrochemicals which have established markets), can be substantiated with the established sustainability criteria of the Renewable Energy Directive, and would provide a strong, reliable and immediate boost to CCU in the sector where it is needed most – the chemical and derived materials industries that will require carbon feedstock also in the long-term.

Avoid creating artificial barriers on using remaining industrial emissions for CCU

Getting out of fossil feedstock as soon as possible should be a clear priority. In order to phase out fossil fuels swiftly and transparently, it is crucial to keep the door open for CCU technologies. Principally, encouraging defossilisation through the promotion of technologies like CCU seems to be a sound approach as it fosters innovation and development in the carbon capture sector.

But, while defossilisation is a crucial priority for achieving net-zero targets, regulations should not enforce defossilisation on the back of needed technologies, in order to avoid creating barriers for their upscaling. The clear threshold in the RED Delegated Act, no longer supporting the production of RFNBO or RCFs from 2042 onwards, could present such a barrier. Considering the investment cycles of industries, a situation is created where companies might not be willing to invest in CCU facilities in a few years, although the timeline for full defossilisation remains uncertain.

While CCU can be a lever for achieving defossilisation, policies should not create barriers that inhibit the development and scale-up of such technologies. Europe should rather agree on the overarching target of defossilisation and drive its achievement via clear targets and regulation focused on this goal, instead of removing incentives for key technologies.

The end game of carbon capture should enable CCU (circularity of carbon) and CDR (removing carbon from the atmosphere)

The main focus of carbon capture technologies should be on utilising the captured carbon either in circular fashion to provide it as a feedstock (CCU) or on actual carbon dioxide removal (CDR) by permanently storing atmospheric and biogenic carbon to balance out the CO_2 level in our atmosphere. Fossil-based CCS is a necessary wild card for balancing out unavoidable emissions where they can be captured – but heavy investments in fossil CCS infrastructure should be carefully compared to alternative options that minimise the emissions gap, such as renewable energy and renewable carbon, and critically look at the risk of fossil lock-in.

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