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Discussion Paper

CO_2 as a Raw Material

A building block of a climate-neutral carbon economy

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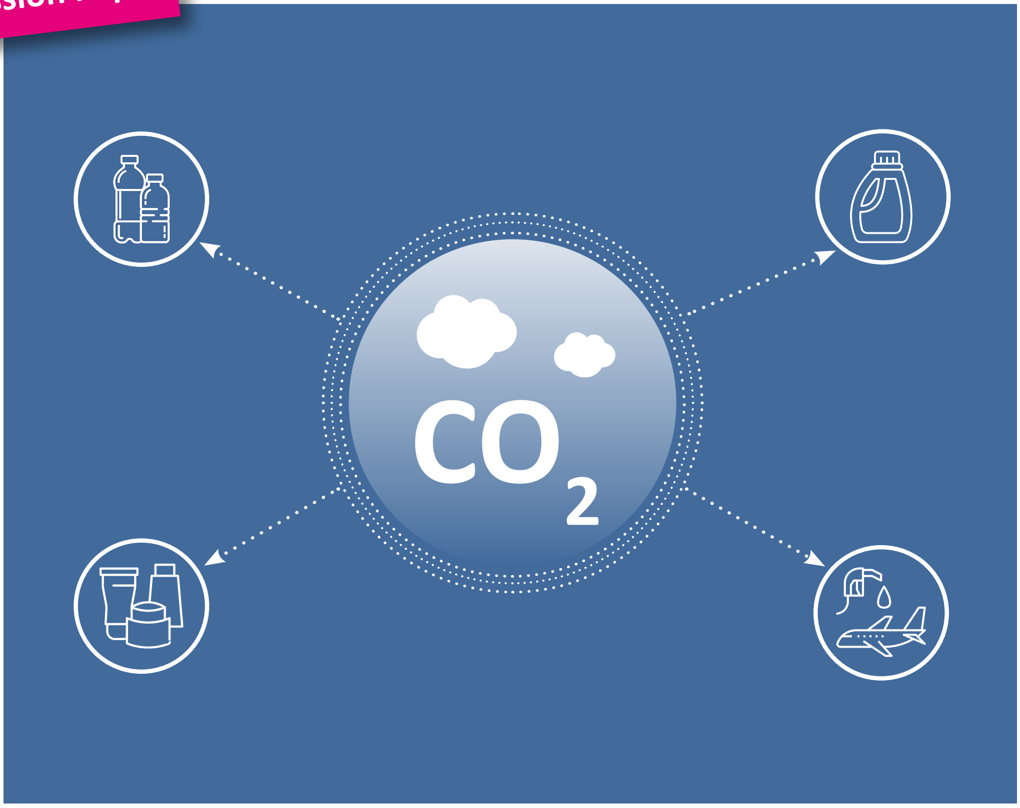
Discussion Paper



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Fact sheet / February 2025

CO₂ as a Raw Material
A building block of a climate-neutral carbon economy

CO₂ as a future carbon source

The chemical industry currently produces carbon-based products such as plastics and detergents primarily from crude oil. At the end of the product's useful life, the carbon from the crude oil is emitted into the atmosphere as CO_2.

In the future, **non-fossil carbon sources or closed carbon cycles** will be required for such products. Biogenic sources and recycling will probably not be sufficient for this, which is why the provision of carbon from CO_2 will also be important in the future. This is referred to as **Carbon Capture and Utilization (CCU)**. The CO_2 can come directly from the atmosphere or from bioenergy facilities. Emissions that are difficult to avoid from fossil or mineral sources could also play a role as a carbon source, especially during a transition period.

CCS and CCU complement each other

Capturing and geologically storing CO_2 **(Carbon Capture and Storage, CCS)** prevents hard-to-abate CO_2 created by industrial processes from being emitted into the atmosphere. Negative emissions are achieved if atmospheric or biogenic CO_2 is stored. **CCU has a different function** – it unlocks another source of carbon, thereby replacing fossil raw materials in industrial manufacturing.

It is likely that both will be needed if we are to achieve a carbon-neutral industry. Experts expect that CCS will be the main method used. However, CCS and CCU should be considered together when **planning the infrastructure** for CO_2 transportation.

Complex carbon footprint

CCU replaces fossil raw materials, meaning that under certain conditions it can contribute to climate change mitigation.
CCU is **not carbon-neutral per se** – if CO_2 captured from fossil or mineral sources is used, its release into the atmosphere is merely delayed for the duration of the product's useful life or for the amount of time it remains in closed recycling loops. In order to make the best possible use of various CCU solutions in the industrial transformation, their impact on the climate must be both assessed in a differentiated manner and controlled by economic incentives. This is challenging from a regulatory perspective, especially if the administrative burden is to be kept to a minimum.

High energy demand

In addition to CO_2, CCU requires hydrogen, for example, to produce methanol – a key raw material for the chemical industry.
Producing this in a carbon-neutral manner, using electrolysis, requires a lot of electricity. If atmospheric CO_2 is used, a high amount of energy is also needed to capture it. Experts view the availability of hydrogen and renewable electricity as the most significant limiting factors for CCU.
This therefore raises the questions as to **the extent to which CCU will be implemented in Germany**, the extent to which sections of the chemical industry will relocate to sites with low-cost renewable energies, and to which "green" raw materials will be imported into the country.

Enabling market ramp-up, avoiding a fossil fuel lock-in

A regulatory framework for CCU should be developed in the near future and should take the following points into account:

- ➢ The market ramp-up of CCU demands targeted funding.
- ➢ The extent to which fossil/mineral CO_2 can be useful for CCU applications in the interim should be investigated in more detail.
- ➢ CCU is necessary to a certain extent, but due to the high energy demand it is also an expensive option for climate change mitigation, even in the long term. This means that reducing the hydrocarbon demand, achieved by increased recycling and by using products that contain carbon more sparingly, for example, should definitely be prioritised.

Glossary

Atmospheric CO_2	CO_2 captured from the atmosphere using direct air carbon capture.
Bulk chemicals	Bulk chemicals, also referred to as basic chemicals or commodity chemicals,are chemical substances produced in large quantities and form the foundation for the chemical industry and the subsequent industrial value chain.
Biogenic CO_2	CO_2 captured during biomass manufacturing, for example from biomass combustion exhaust gases or biomethane generation. Biogenic CO_2 comes from the atmosphere and is absorbed by plants through photosynthesis.
BECC – Bioenergy with Carbon Capture	Bioenergy with carbon capture. How it works: plants absorb CO_2 from the atmosphere through photosynthesis and use it to form energy-rich carbon compounds. These are used to generate electricity, heat or fuel. The CO_2 that is released in the process is not emitted back into the atmosphere, rather it is captured and either stored permanently underground (BECCS – Bioenergy with Carbon Capture and Storage) or utilised (BECCU – Bioenergy with Carbon Capture and Utilization).
CBAM – Carbon Border Adjustment Mechanism	The European Union implements the Carbon Border Adjustment Mechanism (CBAM) to tax carbon-intensive imports by levying a charge equal to the EU's carbon price. The CBAM is designed to offset competitive disadvantages that European industry faces compared to countries with less stringent climate protection policies.
CCS – Carbon Capture and Storage	CO_2 released by power or industrial plants is captured and permanently stored underground (also known as geo-sequestration). Depleted oil and natural gas reservoirs along with deep saline aquifers are the main option for as storage sites.
CCU – Carbon Capture and Utilization	CO_2 capture and utilization. CO_2 is captured, for example from industrial plants or from the atmosphere, for use in chemical processes. With CCU, various products containing carbon can be manufactured, for example plastics, chemicals or what are known as e-fuels, which are synthetic fuels derived from hydrogen and CO_2. The CO_2 replaces mineral oil or natural gas as a carbon source. CO_2 is also used directly (e.g. in the beverage industry) and deployed to increase the yield of fossil hydrocarbons ("Enhanced Hydrocarbon Recovery"). Furthermore, CO_2 can be bound in carbonate in building materials.
CDR – Carbon Dioxide Removal	The removal of CO_2 from the atmosphere, for example through bioenergy with CCS or afforestation, in order to offset remaining emissions and reduce the levels of CO_2 in the atmosphere.
Commodity	The designation for standardised goods.
DACC – Direct Air Carbon Capture	CO_2 extraction technology that uses chemical binders in technical facilities to capture CO_2 from the ambient air. The CO_2 can then be stored geologically (DACCS – Direct Air Carbon Capture and Storage) or utilised (DACCU – Direct Air Carbon Capture and Utilization).
E-fuels	Synthetic fuels that are produced from water and CO_2 using electricity. By using renewable electricity, e-fuels can have a lower climate impact than conventional fuels.
End-of-life emissions	End-of-life emissions are a product's carbon emissions that arise after its useful life has ended, i.e. during disposal, recycling or landfilling.
Feedstock	Feedstocks are chemical and biogenic energy sources (hydrogen and hydrocarbons) that are not used to supply energy, but rather as raw materials, for example as base materials for producing chemicals or plastics. Fossil feedstocks, such as natural gas or refinery by-products like naphtha, are commonly used today.
Fischer-Tropsch synthesis	A chemical process in which hydrocarbons, such as paraffins and olefins, are produced by reacting carbon monoxide and hydrogen at high temperatures and pressures. These can be used as synthetic fuels or chemicals.
Fossil CO_2	Fossil CO_2 is produced by burning fossil fuels such as mineral oil, natural gas or coal and contributes to the increase in greenhouse gas concentrations in the atmosphere.
Green	The term "green" is used here to refer to products that are manufactured using renewable energy sources and environmentally friendly processes, such as the use of green hydrogen in the production of green ammonia, methanol or naphtha.

HVC – High Value Chemicals	The main products of the steam cracking process, olefins and aromatics, are grouped under the term “High Value Chemicals” (HVC). They are used as what are known as platform chemicals in the manufacture of plastics, paints, solvents and other products. Steam cracking breaks down longer-chain hydrocarbons, particularly naphtha from oil refineries. In order to facilitate the carbon-neutral manufacture of HVC in the future, alternative production methods based on hydrogen and carbon, obtained in a carbon-neutral manner are needed.
Carbon management	Carbon management aims to prevent CO_2 which is generated e.g. in an industrial process from being released into the atmosphere or remove emitted CO_2 from the atmosphere, either to prevent it from contributing to global warming or to offset remaining greenhouse gas emissions. Another goal is to make carbon available for product manufacturing without using fossil raw materials.
Lock-in effects	Lock-in effects occur when a technology or structure is retained long-term due to existing circumstances (e.g. established infrastructure or investments that have already been made), even if better alternatives are readily available.
Market pull mechanisms	Market pull mechanisms describe the process by which market demand and requirements for a product drive innovation and product development.
Methanol	Methanol, a flammable alcohol, is an important bulk chemical. Among other things, it is processed into formaldehyde, which in turn is a base material for pharmaceutical products, resins and dyes. It can also be processed into aromatics and olefins. Furthermore, it can be used as a transport fuel, for example as a substitute for heavy fuel oil in shipping. Methanol is considered “green” when only renewable energy sources are used in its manufacture.
Mineral CO_2	Mineral CO_2 is CO_2 that is released when processing minerals such as limestone. An important source is burning cement clinker. Carbon in its stable form that was previously bound in rock masses is converted into CO_2 in a process similar to the combustion of fossil raw materials. Its release increases the CO_2 concentration in the atmosphere and contributes to climate change.
Naphtha	Naphtha is the untreated petroleum distillate from crude oil or natural gas refining and is often used as a raw material in petrochemicals. Naphtha is considered “green” when it is derived from renewable raw materials such as biomass or vegetable oil and then only if renewable energy sources are used in its manufacture.
Net emissions	This is the amount of greenhouse gases that are emitted into the atmosphere minus CO_2 that is removed from the atmosphere (e.g. through afforestation or DACCS). Net negative emissions mean that more CO_2 is removed from the atmosphere than is emitted over the same period.
Polymers	Polymers are chemical substances consisting of macromolecules with repeating structural elements. They occur naturally, but are also produced synthetically. Plastics are made of polymers.
RCF – Recycled Carbon Fuels	RCFs are defined in the EU’s Renewable Energy Directive (RED II) as fuels produced from fossil waste that cannot be avoided, reprocessed for reuse or otherwise recycled. They must reduce greenhouse gas emissions by at least 70 per cent compared to a fossil reference fuel set out in RED II and, depending on the EU member state, can count towards the renewable energy quotas in the transport sector as specified in RED II.
RFNBO – Renewable Fuel of Non-Biological Origin	RFNBOs are defined in the EU’s Renewable Energy Directive (RED II) as fuels produced from renewable energy sources other than biomass. They must reduce greenhouse gas emissions by at least 70 per cent compared to a fossil reference fuel set out in RED II and can count towards the renewable energy quotas in the transport sector as specified in RED II.
Recycled materials	Recycled materials are materials that are obtained from recycled waste and that are then reintroduced as raw materials into the manufacture of new products.
Scope 3 emissions	Scope 3 is the third and most extensive scope for companies to account for their emissions and includes all indirect greenhouse gas emissions from sources that the reporting company does not own or directly control. These arise from upstream and downstream activities along the value chain, such as the transportation of goods or the disposal of products by end users (also known as end-of-life emissions).
Steam cracking	This is a thermal process that uses steam to spit hydrocarbons into smaller molecules such as ethylene, propylene and other olefins. It takes place at high temperature and high pressure.

1 Introduction

Many everyday products contain carbon – examples are various plastics, detergents and cosmetics. Today, these are mostly made from the fossil raw materials mineral oil and natural gas. At the **end of their useful lives**, the carbon in these products is usually emitted into the atmosphere in the form of carbon dioxide (CO_2), thereby contributing to climate change. It is estimated that the carbon contained in chemical industry products accounts for 50 to 55 per cent of the total CO_2 emissions over the life cycle of these products. [1; 2] According to the “Roadmap Chemie 2050” study, the “end-of-life emissions” generated by chemical industry products were responsible for around 7.8 per cent of Germany’s greenhouse gas (GHG) emissions in 2020. [1]

If Germany is to become greenhouse-gas-neutral by 2045, alternative carbon sources that can be used in a carbon-neutral manner will be required in the future. In addition to the use of biomass as a raw material and chemical and mechanical recycling, what is known as **Carbon Capture and Utilization (CCU)** is an option – this is the use of CO_2 captured from industrial processes or the atmosphere.

CCU is one of the three components of what is known as **carbon management** (see Figure 1). In February 2024, the German federal government presented thekey principles for a Carbon Management Strategy (CMS)[1] [3], on the basis of which the CMS is to be developed. With the Industrial Carbon Management Strategy, also published in February 2024, [4] the EU Commission has set ambitious targets for the development of a climate-neutral carbon economy in Europe.

Carbon Capture and Utilisation (CCU)	Carbon Capture and Storage (CCS)	Carbon Dioxide Removal (CDR)
CO_2 is introduced into an additional utilisation cycle, typically for the production of carbon-based products, replacing fossil resources.	CO_2 is captured and permanently stored, preventing the release of CO_2 into the atmosphere.	The removal and subsequent permanent storage of CO_2 from the atmosphere creates a negative emissions balance.

Figure 1: Components of carbon management. Source: authors’ own work.

When CCU is spoken of, it usually refers to its **use as feedstock in the chemical industry** and for the **manufacture of synthetic fuels**, although the majority of the CO_2 captured and used today is applied to boost the yield when extracting fossil hydrocarbons (“Enhanced Hydrocarbon Recovery”). However, in view of the foreseeable end of oil and gas production, this use will become obsolete in a few decades. Small quantities of CO_2 are also used directly, for example in the beverage industry or in agriculture. Furthermore, CO_2 can be bound in carbonate in building materials. Since CO_2 is usually stored here over a long period of time and the CO_2-intensive product cement is substituted, the impact on the climate is promising. [5] This publication focuses on the use of CO_2 as a carbon source in the chemical industry and for the manufacture of synthetic fuels.

In April 2024, the ESYS Academies’ Project published a report on carbon management, which discusses challenges and the need for improvement in the government’s key principles for the CMS. [6] A major point of criticism the ESYS experts had was that the key principles do not differentiate sufficiently between CCU and Carbon Capture and Storage (CCS). Furthermore, the key principles of the German CMS did not focus on the potential of CO_2 as a raw material – unlike the EU Commission’s strategy, which develops a vision

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[1] As of early December 2024, only internal government drafts were available.

for an internal market for captured CO_2 and sees industrial carbon management after 2040 as an “integral part of the EU’s economic system”. [4] According to information available, however, it can be assumed that CCU’s potential contribution to meeting the chemical industry’s carbon demand – and therefore its significance for industrial policy – will also be more strongly addressed in the CMS. Nevertheless, **many questions remain** regarding the possible climate-neutral use of carbon for materials and, in particular, the role of CCU. CCU is still relatively unknown to the general public and so far scenario studies for a carbon-neutral Germany have afforded relatively little attention to the topic, although, in some of the scenarios, products manufactured using CCU are imported on a large scale.

In order to shed more light on the topic, ESYS has compiled the state of knowledge and unanswered questions from interviews and a workshop with experts from science, industry and environmental organisations (see Participants).[2] The results are summarised in this report. Simultaneously, the “Verfahren zur klimaneutralen Bereitstellung und Verarbeitung von Kohlenstoff” study (German only) [7], commissioned by ESYS and carried out by DECHEMA e.V., is being published. This study analyses present-day carbon flows and their development trends and provides an overview of the state of existing CCU technologies.

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[2] This report does not reflect the views of individual interviewees or participants in the workshop. It was written by the named authors following the interviews and the workshop, taking the results of the interviews and the workshop into account.

2 Future carbon demand

2.1 For which products will carbon be needed in the future?

A large proportion of the carbon in circulation worldwide is used for providing energy and in the mobility sector (see Figure 2). Almost all of the carbon used comes from fossil sources (coal, mineral oil, natural gas). About ten per cent of the carbon used is used in **materials**. Of this, just over half (710 million tonnes from "chemicals and derived materials" and "heavy fuel oil fraction") is used in the **chemical industry**. Most of the carbon today comes from fossil sources. Moreover, timber structures and furniture, paper and pulp, as well as textiles contain carbon based on biomass. [8]

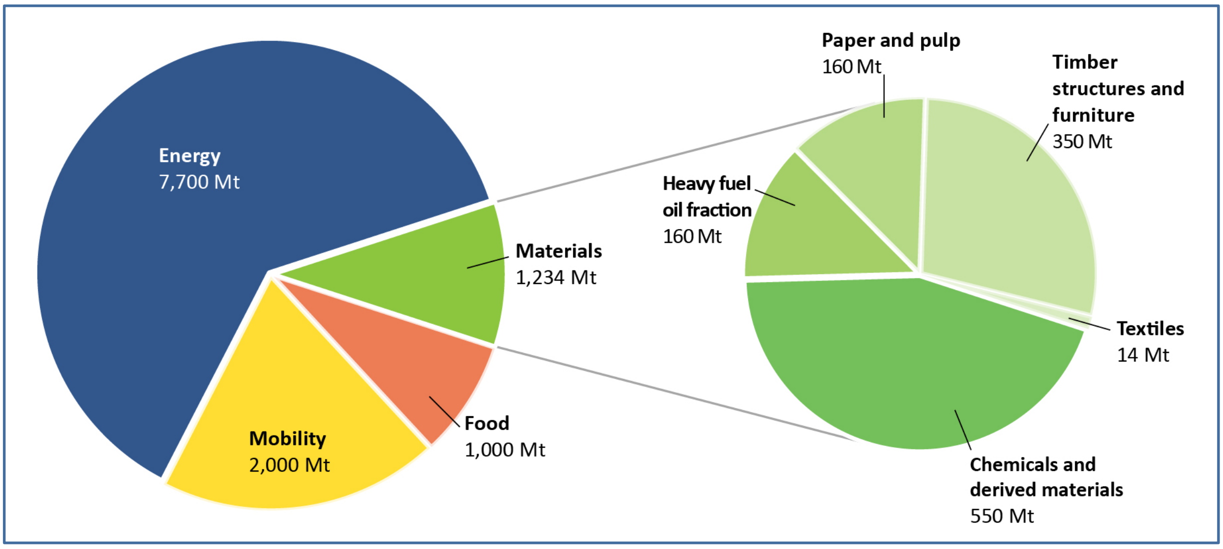

Figure 2: Annual global carbon flows in million tonnes (Mt) by consumption sector (reference years 2015–2022). "Heavy fuel oil fraction" includes bitumen, lubricants and paraffin waxes used in the chemical industry. Source: Kähler et al. 2023 [8]; authors' own work.

In a carbon-neutral world, carbon-based products from the chemical industry will still be required. **Polymers**, especially plastics, are versatile and will continue to be needed in the long term, for example in construction, vehicle manufacturing, packaging and electronics. Demand for **fine and speciality chemicals**, such as dyes, **detergents** and **personal care products**, will also continue in the future, as will the need for **pharmaceutical products**.

It is also foreseeable that **synthetic fuels** will be used more and more in the future – in addition to ammonia, a variety of carbon-based synthetic fuels can be utilised for this purpose. Scenario studies for a carbon-neutral Germany [9; 10; 11; 12; 13; 14; 15] assume that intercontinental aviation and shipping in particular will require synthetic fuels if they are to achieve transition to carbon-neutrality. With the "ReFuelEU Aviation" and "FuelEU Maritime" EU regulations, binding requirements for the use of synthetic fuels in these sectors will be in place starting in 2025.

2.2 What will future carbon demand depend on?

A precise forecast of future carbon demand is virtually impossible due to the large number of influencing factors and uncertainties. The following key factors have been identified:

- **Socio-technical developments**: changes in consumption patterns can lead to an increase or decrease in carbon demand, for example.
- **Technological developments:** the use of synthetic fuels in the transport sector, for example, depends to a large extent on the areas in which direct electric drives offer a more cost-effective alternative.
- **Implementation of a circular economy:** recycling covers some of the carbon demand and reduces the amount of carbon that has to be added to the system. In addition to recycling, other circular approaches are equally important – from reducing the demand for certain products (e.g. through sharing solutions or ease of repair) to material-efficient manufacture and the reuse of components.
- **Economic developments:** the demand for products from the chemical industry is heavily dependent on macroeconomic developments. For example, 18 per cent of these products are used in the construction industry, 12 per cent in the steel and metal industry and 8 per cent in vehicle manufacture. [16]

German and EU industry's carbon demand also depends on **where chemical value-adding processes will take place** in the future. One unanswered question is whether – and, if so, to what extent – industrial processes will be relocated from Germany/the EU to other countries in the future (see Deep dive: Economic significance and carbon footprint of the chemical-pharmaceutical industry in Germany). If carbon-based products (e.g. green naphtha) are imported, fewer feedstocks will have to be produced in Germany.

Existing chemical industry scenarios assume that bulk chemicals – and, in turn, the amount of carbon processed – will remain at today's level **in Germany** by 2050 ("Roadmap Chemie 2050" [1]) or will fall slightly ("Chemistry4Climate" [17; 18]). Different growth rates are assumed for the scenario calculations of the three scenarios that the study commissioned by ESYS and carried out by DECHEMA e.V. presents.

On a **global level**, the Nova Institute assumes that the amount of carbon in products made by the chemical industry will more than double from the current 710 million tonnes to around 1,500 million tonnes per year by 2050. [8] The experts interviewed by ESYS as part of the project also expect a global increase in chemical production and carbon demand. However, given the multitude of influencing factors and uncertainties, quantifying future carbon demand has **considerable uncertainty** associated with it.

Deep dive: Economic significance and carbon footprint of the chemical-pharmaceutical industry in Germany

The chemical-pharmaceutical industry[3] plays a prominent role in Germany, generating a turnover of around 225 billion euros in 2023. [19] This corresponds to a share of around 9 per cent of the turnover of Germany's manufacturing industry[20], making it the third largest industrial sector in the country, after the automotive and mechanical engineering industries. The chemical-pharmaceutical industry in Germany contributes 4.4 per cent of global sales, placing it in third place behind China (40.1 per cent) and the United States (12.0 per cent). [19] In 2023, the German chemical-pharmaceutical industry employed around 480,000 people. [19]

International interdependencies are a particularly salient feature of the chemical-pharmaceutical industry. Chemical products, especially bulk chemicals, are largely traded as uniform commodities. Indeed, Germany's chemical-pharmaceutical industry has benefited from this trend in the past – 62 per cent of the industry's revenue in 2023 came from exports. This means that Germany provides 10.3 per cent of global exports in the chemical-pharmaceutical sector, which is the highest share of any country worldwide. [19]

However, global competition also carries the risk of production being relocated. For example, in 2023, BASF announced the closure of manufacturing facilities in Germany that, unlike their counterparts abroad, had not turned a profit. [21] This was largely due to the increased cost of fossil fuels and feedstocks. In the context of the global transition of the industry towards carbon neutrality, it is foreseeable that the availability and costs of renewable energies will be key factors for investment decisions. Regional differences in the potential and production costs of renewable energies could provide an incentive for relocating manufacture ("renewables pull"). Verpoort et al. [22] estimate that the manufacturing costs for the chemical products urea and ethylene would fall by up to about a third if production were moved from Germany to regions with low production costs for renewable energies. Most of the cost savings are achieved by producing the intermediate products considered in the study (urea: green ammonia, ethylene: green methanol) abroad and importing them. [22] Importing the CCU products is also easier and in all likelihood cheaper than importing hydrogen and processing it into CCU products within Germany. However, CCU in Germany or the EU could reduce dependence on imports and, in turn, contribute to security of supply. These resilience aspects must be weighed against the economic arguments.

Energy-related CO_2 emissions from the chemical-pharmaceutical industry in Germany amounted to 39.6 million tonnes of CO_2 in 2022. [19] This corresponds to about 5.3 per cent of the GHG emissions that were emitted in Germany in 2022. The electrification of processes in the chemical industry plays a crucial role in reducing these manufacturing-related CO_2 emissions. [2] In addition, the carbon bound in the products made by the chemical industry causes considerable CO_2 emissions when they are recycled for energy at the end of their useful lives (end-of-life emissions). End-of-life emissions are crucial to estimating the ecological significance of the feedstock change in the chemical industry, even though they are attributed to waste incineration (and, in turn, the waste or energy industry) according to the source principle of the accounting conventions used in, for example, emissions trading and national GHG footprints. Estimates suggest that end-of-life emissions account for around 50 [1] to 55 per cent [2] of the chemical industry's current CO_2 emissions in Germany. The "Roadmap Chemie 2050" study assumes

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[3] Many statistics report on the combined figures for both sectors (chemical and pharmaceutical industries). In 2023, the chemical industry accounted for 74 per cent (167 billion euros) of the chemical-pharmaceutical industry's sales. Where information refers specifically to the chemical-pharmaceutical industry, this report shall use the term "chemical-pharmaceutical industry". In all other cases, the term "chemical industry" is used.

that end-of-life emissions in 2020 amounted to 56.5 million tonnes of CO_2 equivalents, which accounted for 7.8 per cent of Germany’s greenhouse gas emissions in 2020. End-of-life emissions represent a significant share of the chemical industry’s Scope 3 emissions, but they are not the same as Scope 3 emissions, because the latter also include, among other things, upstream emissions, such as those from the extraction and transportation of fossil raw materials. International estimates assume that around 75 per cent of the chemical industry’s emissions are Scope 3 emissions. [23] The transition of the chemical industry to carbon neutrality must therefore address the entire life cycle of the products.

3 Future carbon sources

Today, 85 per cent of the carbon in chemicals and polymers worldwide comes from **fossil raw materials**, while biomass and recycling account for a rather small share of 10 and 5 per cent respectively. [12] In order to end the use of fossil raw materials, it is necessary, on one hand, to make greater use of climate-neutral carbon sources such as **biomass** and **recycling** (especially of plastics). On the other hand, the **use of CO_2** (CCU) should be considered as an option. Figure 3 provides an overview of the various carbon sources and the associated carbon flows using plastic products as an example. When using CO_2, the carbon footprint depends on whether the CO_2 is derived from fossil/mineral sources, from biomass or from the atmosphere (see Section 4.2). In principle, the use of fossil raw materials is also conceivable in a carbon-neutral future if the CO_2 is captured and stored geologically at the end of the products' useful lives (e.g. during waste incineration), or if the CO_2 emissions caused are offset by removing CO_2 from the atmosphere.

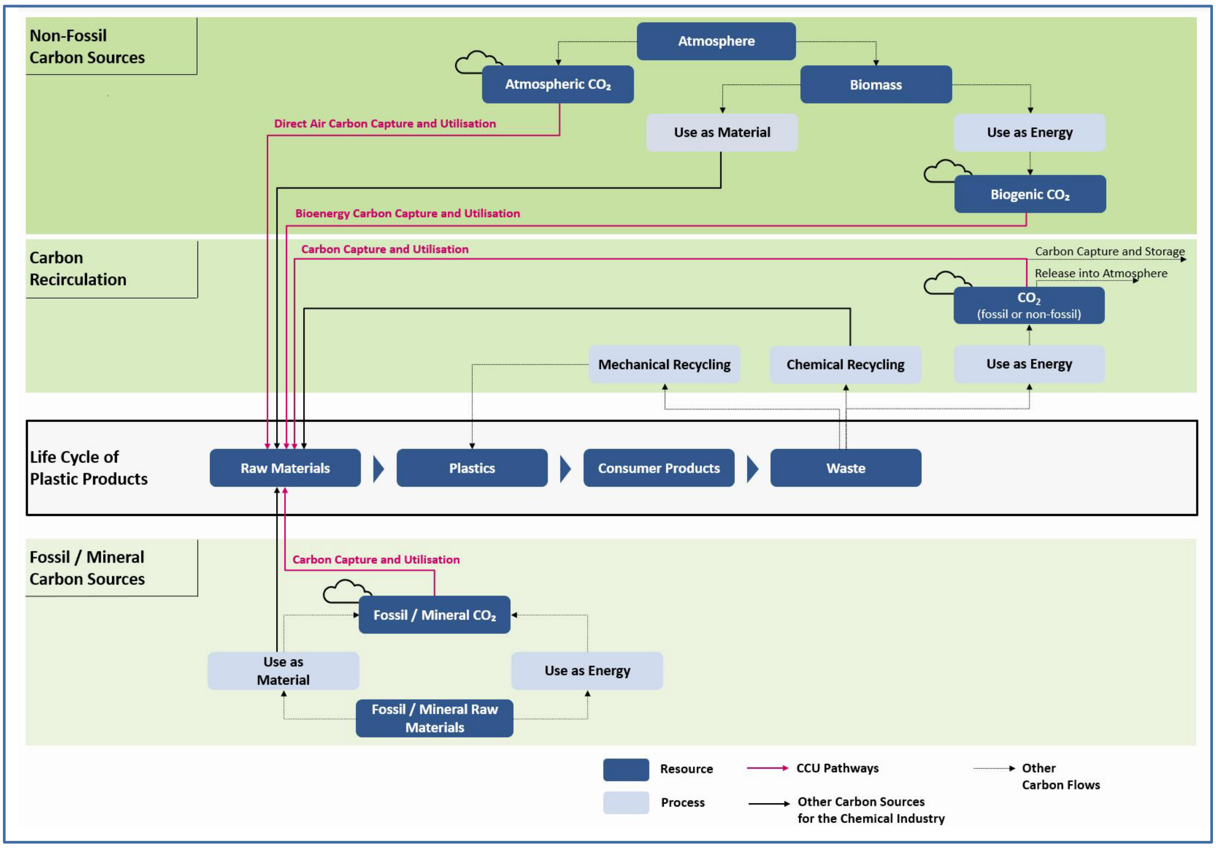


Figure 3: Possible carbon sources and flows using plastic products as an example. Paths involving the use of CO_2 (CCU) are marked in pink. Source: authors' own work.

3.1 What fossil and mineral carbon sources are available?

Naphtha, a refinery by-product, is currently the most prevalent feedstock in organic chemistry, with a share of 71.5 per cent [17]. Naphtha is broken down into shorter-chained hydrocarbon compounds and aromatics by means of steam cracking. These products, known as high value chemicals (HVC) or platform chemicals (e.g. ethylene), are then processed into plastics, paints, varnishes, solvents and other products. Given that the increased use of electric vehicles will reduce the demand for fuel in the future, the manufacture of fossil naphtha in refineries will also decline. This is another reason why switching to alternative feedstocks is necessary. Since there is very close interaction between various branches of industry and production processes, the impending industry transformation will have a significant impact on bulk chemical value chains.

One alternative to the direct use of fossil raw materials as feedstock is to **process hard-to-abate CO_2 from fossil or mineral sources**, especially from cement and lime production and thermal waste recycling. While binding the CO_2 in products does not stop it from being released completely, it does delay its release. The climate change mitigation effect therefore depends very much on how long the CO_2 remains in the product (i.e. the product’s useful life) and what happens to the product (i.e. the CO_2) when its useful life comes to an end (see Section 4.2). Since it is not usually possible to capture all of the CO_2, there will also be a certain amount of residual emissions that need to be taken into account in the carbon footprint. Studies on the chemical absorption of CO_2 from flue gases with monoethanolamine show that CO_2 capture rates of over 95 per cent are technically feasible. [24] Since energy consumption and costs increase with the capture rate, capture rates achieved in practice are a question of economic efficiency, if nothing else.

Deep dive: Production routes for the manufacture of bulk chemicals using CO_2

Two routes can be considered for the manufacture of HVC with CO_2, as shown in Figure 4. On one hand, Fischer-Tropsch synthesis can be used to produce naphtha, which is currently used primarily as a feedstock in the chemical industry. On the other, methanol can be synthesised and used as a base material for other applications.

Whichever route is most favourable depends on the products to be manufactured. Fischer-Tropsch naphtha can be integrated into existing processes as a direct substitute for fossil naphtha. [17] However, methanol, which is already a key base chemical, can be preferable for some products. [17; 25] Among other things, methanol can be used directly as a fuel or fuel additive (e.g. as a substitute for heavy fuel oil in shipping). [25]

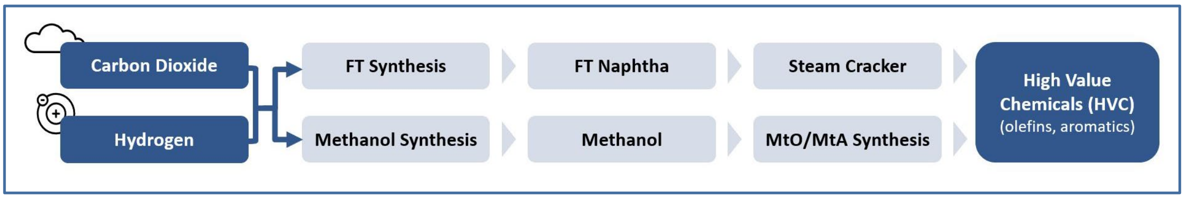


Figure 4: Routes for the manufacture of bulk chemicals using CO_2 and hydrogen. FT stands for Fischer-Tropsch. MtO stands for methanol-to-olefins. MtA stands for methanol-to-aromatics. Source: authors' own work, adapted based on FfE figures [26].

In scenario studies for a carbon-neutral Germany, the demand for methanol increases by 2045 in all scenarios considered because naphtha is increasingly replaced by methanol in HVC production. [27] In some scenarios, the chemical industry still uses fossil naphtha in 2045.

In addition to CO_2, the processes also require large quantities of hydrogen. This is produced by electrolysing water, which requires a great deal of energy. The reaction of hydrogen and CO_2, which ultimately produces the hydrocarbons, also requires energy. This is independent of how efficient the processes employed actually are. In addition, energy losses of these processes must be covered. The high energy demand is an inherent disadvantage of CCU.

3.2 What are climate-neutral carbon sources?

Climate-neutral carbon sources are based on CO_2 from the atmosphere, which has either been photosynthesised by plants and thus converted into biomass or obtained through direct air carbon capture (DACC) technology. In the following, CO_2 obtained through DACC is referred to as "atmospheric", and CO_2 obtained from biomass processing as "biogenic", although the latter was originally also absorbed from the atmosphere by vegetation.

Biomass as a carbon source has the great advantage that it consists of energy-rich hydrocarbon compounds, similar to fossil raw materials. This means that much less additional energy is required for processing it into chemical products than when using CO_2 as a carbon source. Another advantage is that it has a hitherto wide range of applications in the chemical industry, meaning that we have already gained considerable experience in processing it. In addition, it is possible to switch gradually to biomass in some chemical industry processes, since up to a certain percentage of biomass can be added to the fossil feedstocks, for example in steam crackers or synthetis gas plants, without requiring technical modifications to the facilities. However, the **potential for sustainably usable biomass** is limited due to the amount of land required for its cultivation. Furthermore, the use of biomass is not generally carbon-neutral when viewed over its entire life cycle. The type of land management in particular and its usage has a significant impact on the carbon footprint. For instance, greenhouse gas emissions from agricultural management result from the cultivation of agricultural crops such as corn or rapeseed (examples are nitrous oxide emissions from fertilisers, emissions from the use of energy sources for cultivation, harvesting, etc.). A decrease in the carbon stocks stored in vegetation and soil also causes greenhouse gas emissions. This is the case, for example, when more wood is removed from a forest than grows back, or when grassland is converted into arable land. [28]

Due to the problematic ecological effects of cultivating energy crops and the increasing use of wood from forests, experts advocate the use of **biogenic waste and residual materials** as a priority. [29] This also offers a particularly high potential for reducing greenhouse gas emissions [28]. The increased use of sewage sludge or food waste could unlock additional potential for this. In addition, there is considerable competition for the use of biomass (including for the provision of process heat in industry). The experts interviewed by ESYS therefore consider it sensible to prioritise the use of biomass as a material. A more cascading use is of particular interest – first as a material, then as an energy source. In carbon neutrality scenarios for Germany, the generation of electricity and heating from biomass in particular is reduced by 2045, while biomass is used to a considerable extent as an energy source in transport (especially for international aviation and shipping) and to generate process heat. [25]

An alternative to the direct material use of biomass is the use of **CO_2 from bioenergy installations** for CCU (Bioenergy with Carbon Capture and Utilization, BECCU). Approximately two million tonnes of CO_2 are currently captured from BECC installations worldwide. [30] While the costs of CO_2 capture depend on both the local conditions and how the biomass is used, they are significantly lower than for CO_2 capture from the atmosphere. [25]

- In some carbon neutrality scenarios, biomass is used on a large scale to generate **high-temperature process heat in industry**. [10] CO_2 capture is an option here because relatively large quantities of CO_2 are produced. Moreover, it is possible that the industrial sites may be connected to a CO_2 transportation infrastructure anyway. There may also be opportunities to use the CO_2 on site.
- **Biogas facilities** are also technically well suited for CO_2 capture, since the CO_2 concentration in biogas, at 25 to 45 per cent [31], is considerably higher than in combustion exhaust gases. For facilities that feed biomethane into the natural gas grid, the CO_2 must be captured during the processing of the biomethane anyway. However, the economic viability of this CO_2 source is questionable, as the quantities of CO_2 produced per biogas facility are relatively small. In many cases, connecting to a CO_2 pipeline would probably be too expensive, due to the fact that the facilities are usually located in rural areas. It would be necessary to determine whether transportation by lorry would be a viable option. Furthermore, the extent to which biomethane will play a role in the future energy system is unclear.
- Another option is **bioethanol facilities**, where high-purity CO_2 is produced. More than 90 per cent of the BECC facilities in operation worldwide are bioethanol facilities. [30]

Direct **capture of CO_2 from the atmosphere using DACC facilities** is by far the most expensive and energy-intensive option for capturing CO_2 available today. This is mainly due to the low CO_2 content in the air, but also to the low level of technological development and the sizes of the capture facilities constructed to date – to capture one cubic metre of CO_2, at least 2,500 cubic metres of air must be “filtered”. So far, there are only 27 DACC facilities worldwide, which collectively filter less than 0.1 million tonnes of CO_2 per year. 130 DACC facilities are currently in the planning stage, but only 15 of these are at an advanced stage of development. [32]

According to company representatives, capture costs currently range from 600 to 900 euros per tonne of CO_2. Experts interviewed by ESYS hope that, through further development and upscaling of the technology, these costs can be reduced to 150 to 200 euros per tonne by 2050. However, cost projections indicate a high degree of uncertainty in long-term cost development. [33; 34] In view of the high energy demand, the experts interviewed by ESYS consider it rather unlikely that CCU with atmospheric CO_2 will be implemented in Germany by 2050. However, in the case of DACC processes that use heat at low temperature levels as an energy source, some of the energy demand could be covered with waste heat. The various DACC processes differ in terms of the temperature required and the ratio of electricity to heat demand.

3.3 How can carbon be recycled?

Carbon recycling can reduce the need for “fresh” carbon (from fossil raw materials, biomass or atmospheric CO_2) for the production of HVC. Today, **mechanical recycling**, in which sorted plastic waste is melted down and processed into new products, is used almost exclusively. Indeed, in 2021, about 35 per cent of all plastic waste collected in Germany was recycled, of which approximately 99 per cent per cent was mechanically recycled. [35] However, high-quality recycled materials can only be obtained from from sorted waste streams with minimal impurities. Furthermore, it is not yet possible to keep the plastics in the cycle for an unlimited period, as the recycling process damages the polymer chains each time.

In addition to mechanical recycling, there are various **chemical recycling processes** that break plastic waste down into its chemical components. Depending on the process used, the plastics are broken down to a greater or lesser extent into polymers, monomers or (in the case of gasification) into synthesis gas containing hydrogen and carbon monoxide. [2]

The **costs** of recycling processes vary greatly depending on the process used and the recycled product. [36] Furthermore, chemical recycling processes are still in the development stage, making it difficult or impossible to make an accurate estimate of their costs.

Increasing the recycling rate is also important because the **energy demand** for recycling is often significantly lower than for production using primary raw materials such as crude oil or biomass. For example, the majority of manufacturing-related GHG emissions in bulk chemicals are caused by the high energy demand associated with naphtha steam cracking, which requires temperatures of around 800°C. [14] Chemical recycling processes require more energy than mechanical recycling, but place fewer demands on the quality of the material to be recycled. In principle, the lower the process’s energy demand, the higher the demands on the purity of the waste and the lower the tolerance for impurities. [2]

Scenario studies for a carbon-neutral Germany assume that increasing the recycling rate for plastics will reduce the demand for primary production of HVC. [27] While more than half of the plastic waste is incinerated in waste-to-energy facilities today, one scenario from the Forschungszentrum Jülich, for example, assumes that in 2045, 40 per cent of the plastic waste generated in Germany will be recycled mechanically and 60 per cent chemically. [15] DECHEMA e.V. assumes that, in theory, 2.3 million tonnes of plastic waste could be chemically recycled in Germany in 2045. This corresponds to 26 per cent of today’s plastic production or 38 per cent of the plastic waste collected today. The assumption is that more plastic waste will be collected separately in the future. [7] Circular economy approaches that start with the consumer and aim to reduce the demand for plastic products, on the other hand, hardly play a role in these scenarios. These include, among other things, longer and more intensive product use, for example through higher quality, repairability and service or performance models (sharing). [27]

Despite increasing recycling, the scenarios show that there will still be a substantial demand for feedstocks from primary production in 2045. Estimates suggest that the chemical industry’s demand for fresh carbon could only be reduced by just under a quarter, to 8.8 million tonnes per year, if recycling potential were fully exploited. [2] This is partly because 62 per cent of chemical products are exported and, as such, do not enter the German recycling system. [2] On the other hand, products containing carbon, such as vehicles, electrical appliances and toys, are imported on a large scale. An overview of the cross-border carbon flows would be helpful, not least with regard to the recycling potential (see Deep dive: Carbon flows in carbon neutrality scenarios).

If neither mechanical nor chemical recycling is possible, the CO_2 can be **captured during waste incineration** and used for new products via CCU. Since it is not usually possible to capture all of the CO_2, the carbon cycle cannot be completely closed. CCU usually requires more energy than mechanical and chemical recycling does. [2] Currently, about half of the carbon in the waste that ends up in incinerators is biogenic in origin and the other half fossil. The increasing use of biomass and biogenic/atmospheric CO_2 for product manufacturing will increase the proportion of non-fossil carbon in waste streams in the future.

For consumable products that do not end up in waste incinerators, the options for whether carbon can be recovered and, if so, how, vary. For example, while detergents can be recovered in sewage treatment facilities, the decentralised combustion of synthetic fuels makes it almost impossible to capture the resulting CO_2. Carbon recycling is therefore not possible and the CO_2 usually returns to the atmosphere after a short time.

4 Potential contribution of CCU to a carbon-neutral economy

4.1 How much CCU is possible, necessary and adequate?

To date, CO_2 has only been used as a feedstock in **exceptional cases**. Indeed, 44 million tonnes of carbon from CO_2 are used worldwide each year for urea production. Approximately 0.2 million tonnes of carbon from CO_2 are processed for other chemicals (in particular salicylic acid, methanol and cyclic carbonate esters). In addition, 0.07 million tonnes of carbon from CO_2 are used directly for plastic products. [8] The 44.27 million tonnes of carbon from CO_2 used annually worldwide correspond to approximately 161 million tonnes of CO_2. In Germany, CO_2 has also only been used as a feedstock in a few projects to date. This means that the development of large-scale CCU processes for manufacturing products containing carbon (apart from urea production) is still in its infancy. The study conducted by DECHEMA e.V. on behalf of ESYS provides further insights into CCU technologies. [7]

CCU's **limited market penetration** is primarily the result of economic factors – CCU is currently not considered competitive due to high costs, and its future economic viability is also uncertain. The limiting factors are as follows:

- **Fossil carbon sources** are (still) available at low cost and the current regulatory framework provides little incentive for companies to phase out fossil feedstocks (see Section 5.2).
- The costs of CCU are heavily dependent on the costs of the energy used. It is likely that the fully processed feedstocks and e-fuels could be **imported directly from countries with higher wind and solar energy potential** at a much lower cost (see Deep dive: Economic significance and carbon footprint of the chemical-pharmaceutical industry in Germany).
- CCU requires a **transportation infrastructure**. There are currently no CO_2 networks in Germany. How this infrastructure can be developed quickly and efficiently is still up for debate.
- An expansion of CCU in Germany would be associated with a high additional demand for wind energy and photovoltaics for the production of green hydrogen. Therefore, the potential for CCU in Germany is also limited by the **availability of land for renewable energy facilities** – unless it is assumed that the hydrogen required for CCU will be imported. If energy has to be imported anyway due to limited land availability, it is likely to be cheaper and easier to import the fully processed feedstocks and e-fuels than to import hydrogen to Germany and continue to process it using CCU. However, CCU in Germany could reduce dependence on imports and thereby contribute to security of supply. These resilience aspects must be weighed against the economic arguments.

Due to the high energy demand and the high costs, the experts interviewed by ESYS see CCU as a **less favourable option** compared to the continued expansion of both mechanical and chemical recycling and the use of biomass as a feedstock (see Sections 3.2 and 3.3). In addition, a lower demand for goods containing carbon, for example as a result of efforts to reduce the number of throwaway consumer products and to extend the useful lives of products (e.g. by making them easier to repair), would help to limit the required capacities for CCU and the challenges associated with its expansion.

Most of the experts interviewed by ESYS estimate that **only limited capacity for CCU can be established by 2045**. It will be almost impossible to provide additional CCU products on top of feedstocks for the chemical industry and fuels for parts of the aviation and shipping industries. For large parts of the transport sector, therefore, synthetic fuels produced by CCU are an unrealistic alternative to e-mobility.

The **study by DECHEMA e.V.** [7] conducted in parallel with this report makes it clear that the demand for CO_2 for the bulk chemicals rials industry depends very much on the amount of biomass available for use as feedstock. In Germany, the potential for mobilising biomass and chemical recycling in the DECHEMA e.V. scenarios cannot cover raw material industries' carbon demand alone, meaning that CCU or biomass imports would be required. Whether and to what extent biomass can be imported from other European countries for Germany's chemical raw materials industry would need to be analysed in more detail. On one hand, the extent to which unused residual and waste biomass can be tapped is unclear. On the other, local use of waste and residual materials in particular may prove more sensible, meaning that it would be necessary to compare the geographic distribution of the mobilisable biomass potential with the demand. Moreover, the DECHEMA e.V. study does not consider carbon demand from outside the bulk chemicals industry, in particular for carbon-neutral fuels used in aviation and maritime transport. Biomass or CO_2 can also be used as a carbon source to meet these demands, which means that there is also usage competition for biomass here. Overall, there is a high degree of uncertainty as to how much biomass can be used for the bulk chemicals industry in Germany.

Scenario studies for a carbon-neutral Germany show that, in addition to carbon-neutral feedstocks for the chemical industry, the need for carbon-based energy sources will endure to a considerable extent, especially in aviation and maritime transport and for the provision of process heat in industry. The scenarios differ in terms of which of these areas will use the majority of the biomass. Overall, however, the biomass available is not sufficient to cover the entire demand for carbon-based energy sources and feedstocks. Therefore, in addition to recycling and the use of biomass as a feedstock, CO_2 as a carbon source is required in the long term. [27]

The studies also differ when it comes to the question as to whether greenhouse-gas-neutral feedstocks with chemical recycling or from captured CO_2 are produced in Germany or imported. In some scenarios, domestic feedstock production is essentially limited to secondary raw material recovery, for example, pyrolysis oil from chemical recycling of plastic waste (pyrolysis, gasification) [11] and methanol production with CO_2 captured in bioenergy facilities. [12] In these scenarios, the import of green naphtha and methanol produced with atmospheric CO_2 covers a large part of the feedstock demand. Other scenarios presume significant green feedstock production within Germany, leading to substantial demand for CCU. For example, in the German Federal Ministry for Economic Affairs and Climate Action's (BMWK) long-term scenarios, almost all CO_2 from cement and lime works and waste incineration (30 million tonnes in total) is needed to produce methanol and HVC in 2045. [37]

A comparison of two recent scenario studies [38, 39], both of which place a strong focus on the industrial sector, shows that the underlying overall strategies for carbon management differ. In the BMWK long-term scenarios' industrial sector module [38], the focus is on the provision of carbon. In Germany, a large proportion of the CO_2 from cement and lime works and waste incinerators is used for CCU to produce olefins and aromatics for the chemical industry. Since fossil/mineral CO_2 is used on a large scale here to produce products with short useful lives, the carbon footprint must be considered more closely (see Section 4.2). If it is not possible to keep the carbon permanently within the cycle by recycling, this must be offset by negative emissions – this is in addition to the negative emissions that are required anyway to offset residual emissions from agriculture, for example. In the Agora Think Tanks study [39], on the other hand, fossil/mineral CO_2 from cement and lime works and waste incinerators is stored permanently using CCS. Feedstocks for the chemical industry are provided by biomass and chemical recycling of plastic waste, as well as by imported methanol. The production of plastic products from biomass, combined with CCS at the end of these products' useful lives in waste incineration, results in overall negative emissions in the entire chain. These are used to offset residual emissions from agriculture. Due to the high energy demand, CCU is rarely used in the Agora scenario.

Despite the differences described, the scenario studies do agree on some points – CCU will not play any role by 2030. Atmospheric CO_2 is not used for feedstock production in German in any of the scenarios due to the limited potential for renewable energies and the more favourable import options. Alongside the feedstocks for the chemical industry, hydrocarbons produced using CCU are also used as fuels in the scenarios analysed, primarily for aviation and maritime transport. [27] For the most part (80 to 100 per cent), these are imported. [27]

Previous scenario studies for a carbon-neutral Germany do take CCU into account in their model calculations, but relatively little time is usually devoted to the topic when discussing the results (see Deep dive: Carbon flows in carbon neutrality scenarios). This makes it difficult to analyse what causes the rather different results. Therefore, there is still a need for **further research** into the role of CCU in the transition to carbon neutrality. Scenario analyses that provide a systematic investigation of the effects of various parameters on the demand for CCU would be particularly helpful. Among other things, answers to the following questions are required:

- How will the chemical industry's **total carbon demand** in Germany change as a result of new consumption patterns and the implementation of mechanical recycling and other circular economy approaches (see Section 2.2)?
- Will chemical value creation processes shift? To what extent will **feedstocks containing carbon be imported** (see Section 2.2)?
- To what extent can **biomass** be used as a feedstock? Here, competition with energy use and the interrelations with the food system must be taken into account. For example, a more plant-based diet would make more biomass available for use as a feedstock without increasing the area required for biomass cultivation.
- To what extent can **chemical recycling** meet the chemical industry's carbon demand?
- Is the **continued, long-term use of fossil raw materials** in combination with CCS (e.g. the manufacture of plastics from crude oil with CCS during waste incineration) being considered?
- Overall **carbon management** strategy: how are negative emissions achieved?

Deep dive: Carbon flows in carbon neutrality scenarios

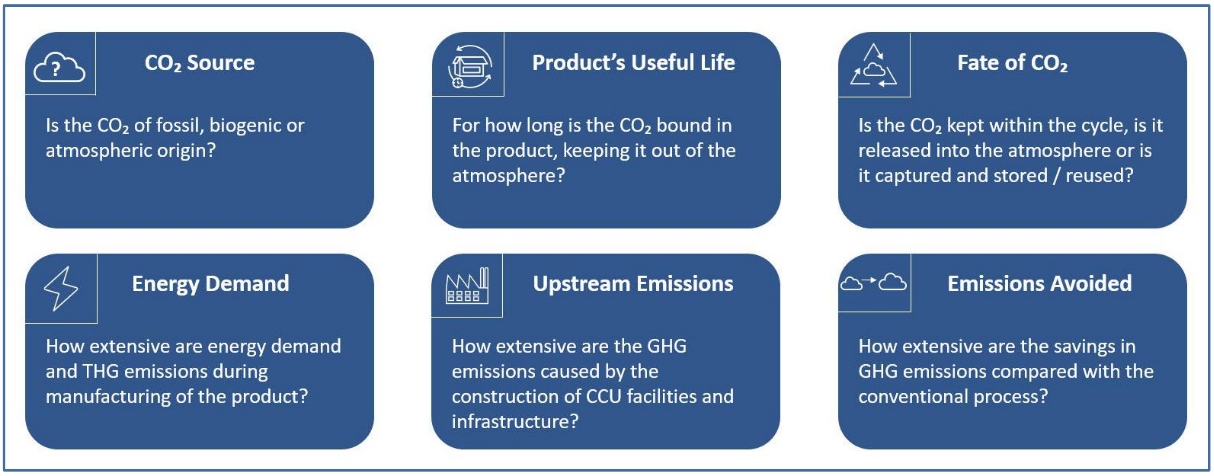
Scenario studies that examine transformation pathways to carbon neutrality often focus on the energy system. The chemical industry is not portrayed in great detail in many energy system models, and its transformation pathway is often illustrated using individual sample products. Since these differ between studies, the results are difficult to compare. [27] Furthermore, relatively little attention is paid to the analysis and presentation of carbon flows. As a result, the chemical industry's complex carbon flows, with their numerous products and intermediate materials, are described incompletely in many studies and are not fully comprehensible. A more detailed representation of the process chains would be particularly helpful for comparing scenarios that place different emphases on both mechanical and chemical recycling and the use of CO_2. Although detailed studies of the useful life assessment of individual products or materials such as plastics are available [40; 41], these aspects have not yet been integrated into studies on the overall transformation of Germany or Europe.

In order to assess the possible role of CCU in the transformation towards carbon neutrality and, in particular, the influence of different CCU approaches on the carbon footprint, more detailed analyses and representations of carbon flows in energy system studies would be helpful. This applies to both the models themselves and the textual and graphical representations in the studies. For example, it is unclear in some cases whether the carbon binding in other countries is credited to the German carbon footprint when imported green feedstocks are used. When synthetic fuels and feedstocks are imported from outside Europe, it is also sometimes unclear which carbon sources are used. CCU and CCS are often grouped together, but it is not clear whether and under what conditions CCU is equated with CCS in the carbon footprint. Information is also often missing on how long carbon remains bound in the CCU products or remains within the cycle by means of recycling, and how the amount of bound carbon in the product develops over time. A breakdown of carbon flows across national borders would also show the extent to which fossil/mineral CO_2 is exported via the export of products containing carbon from Germany and may be released into the atmosphere in the importing country.

Overall, research with regard to a stronger integration of energy system models and material flow models is still required. This could, among other things, help to examine in more detail how DACC and the material and energetic utilization of biomass are integrated into the system. To evaluate and interpret scenario studies, developing a consistent, standardised method of presenting the results of carbon flows from models would be valuable.

4.2 What sort of carbon footprint does CCU have?

Using CO_2 as a raw material can replace fossil carbon sources and, under certain conditions, contribute to mitigating climate change. The impact of CCU on the climate depends on several factors, which are shown in Figure 5.



CO$_2$ Source

Is the CO$_2$ of fossil, biogenic or atmospheric origin?

Product's Useful Life

For how long is the CO$_2$ bound in the product, keeping it out of the atmosphere?

Fate of CO$_2$

Is the CO$_2$ kept within the cycle, is it released into the atmosphere or is it captured and stored / reused?

Energy Demand

How extensive are energy demand and THG emissions during manufacturing of the product?

Upstream Emissions

How extensive are the GHG emissions caused by the construction of CCU facilities and infrastructure?

Emissions Avoided

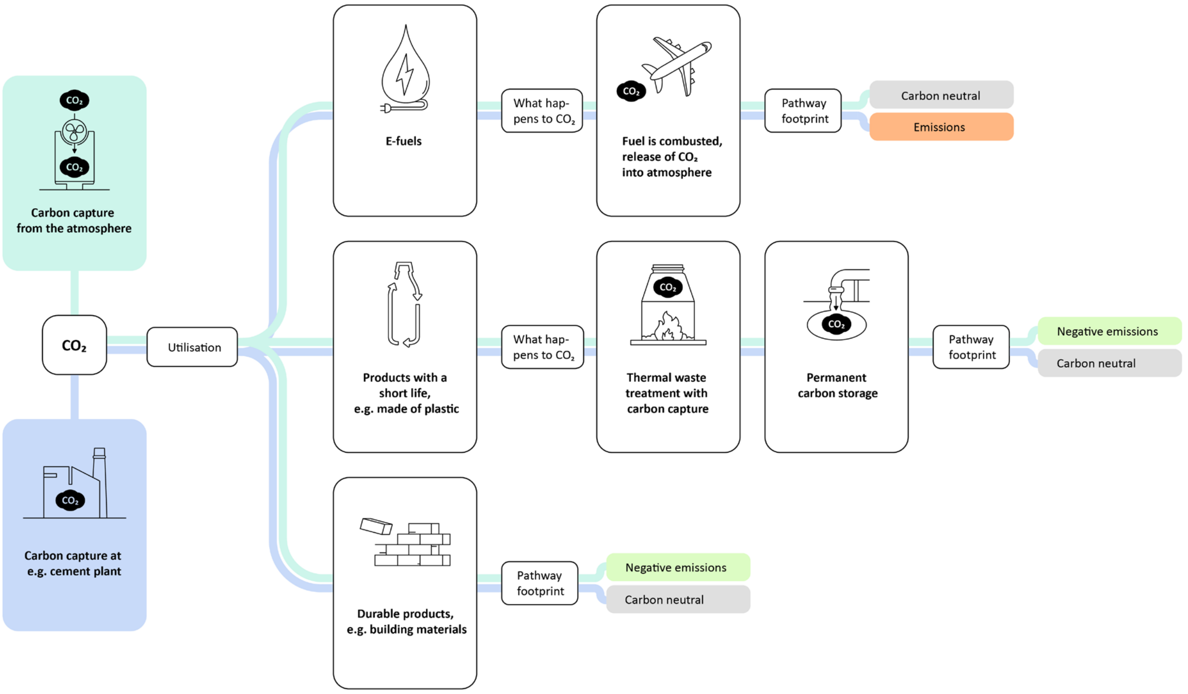
How extensive are the savings in GHG emissions compared with the conventional process?

Figure 5: Factors that influence the impact of CCU on the climate. Source: authors' own work.

Depending on these factors, CCU can **release net emissions** (but may still reduce emissions compared to conventional processes) or be **net carbon neutral** or result in **net negative emissions**. In particular, if fossil/mineral CO$_2$ is used, CCU is generally not carbon neutral overall, rather it only delays the release of the CO$_2$ for the duration of the product's useful life. In a carbon-neutral system, CCU using fossil/mineral CO$_2$ can therefore only be used if the CO$_2$ is kept out of the atmosphere permanently (by using it in products with a very long useful life, by creating a closed and permanent recycling loop or by using CCS at the end of the useful life) or if the CO$_2$ emissions are offset elsewhere with negative emissions (e.g. with DACCS).

Figure 6 is a schematic presentation of different CCU process pathways and examples of applications and their contribution to climate protection. These are categorised according to carbon source, sequestration period and where the CO$_2$ used ends up in the longer term.

Carbon Capture and Utilisation: the climatic impact of using CO_2 as a raw material



CO_2 can be used as a raw material for manufacturing synthetic fuels (e-fuels). These can be used in internal combustion engines, thereby replacing fossil-based fuels, such as petrol, diesel and kerosene

CO_2 can serve as a raw material for a variety of short-life products, such as plastics, paints and varnishes, adhesives, cleaning agents and medicines. Recycling does mean that carbon is bound in products for longer, but complete recycling of product materials is unfeasible, even in the future.

If durable products (e.g. building materials) are made using CO_2, the carbon stays bound in them for several decades.

When fuels are combusted in the transport sector, the release of CO_2 is spread over a large area. This makes it impossible to capture the CO_2 directly at source, so it escapes into the atmosphere.

When short-life products are incinerated at the end of their lifespan, the carbon stored in the product is turned into CO_2 again – although it can then be captured.

The release of CO_2 is avoided if it is captured at the thermal waste treatment plant and placed in long-term storage (CCS).

🟦 Blue pathways indicate the use of fossil CO_2

🟩 Green pathways indicate the use of atmospheric CO_2

Figure 6: Carbon footprint of example CCU pathways. The figure only assesses the source, sequestration period and ultimate destination of the CO_2. Pathways with biogenic CO_2 are not shown, as their carbon footprint is the same as for atmospheric CO_2. Systemic aspects such as the quantity and source of the energy required for the CCU process, GHG emissions for the construction of the facilities and infrastructure, as well as substituted products and production processes are not shown (see also Figure 5). Furthermore, the illustration assumes complete capture of the CO_2. In practice, the potentially carbon-neutral pathways shown here are associated with residual emissions. Source: Energy Systems of the Future (ESYS); Illustration by Figures GmbH.

Even a theoretically conceivable complete recirculation and constant reuse of fossil/mineral CO_2 is not a long-term possibility for using fossil resources continuously and on a permanent basis. Indeed, if additional CO_2 is constantly introduced into the cycle, the stock of products would have to increase continuously in order to bind the additional CO_2. To achieve long-term carbon neutrality, all the CO_2 newly produced from fossil/mineral raw materials and introduced into the carbon cycle must ultimately be offset by the **removal and permanent storage of CO_2** at the end of the product's useful life. This makes CCU a useful supplement to CCS, but not an outright alternative.

4.3 What role could fossil/mineral CO_2 play in the future?

In many cases, CCU with CO_2 from fossil/mineral sources is not carbon neutral. However, it can be useful for a **transitional period** because using CO_2 as a carbon source replaces carbon from fossil sources, thereby reducing emissions. In addition, using CO_2 that is difficult to avoid, such as that from cement works and waste incinerators, could simplify the market ramp-up of CCU. This is because these facilities produce large quantities of CO_2 and will probably be connected to a CO_2 transportation infrastructure anyway.

It is still unclear whether sufficient **carbon-neutral alternatives** will be available in the medium term – the extent to which biogenic CO_2 is available and the associated costs should be analysed in detail. Today, biomass is largely processed in small decentralised facilities, where the capture and transportation of CO_2 is likely to incur higher costs than in cement works or waste incinerators. According to the industry representatives interviewed by ESYS, procuring biogenic CO_2 is a hurdle for CCU projects. What is certain is that atmospheric CO_2 will initially only be available in small quantities and at very high costs, which means that it will not play a significant role as a carbon source for CCU, at least in the medium term.

According to experts, it is unlikely that CCU will be implemented on a significant scale before 2030; by 2045 (in Germany) or 2050 (in the rest of the EU), production processes would have to be converted to biogenic or atmospheric CO_2, or permanent CO_2 storage would have to be ensured (in products with long useful lives or via CCS at the end of the product's useful life). The current **time window of only 15 to 20 years** makes investments in **transitional solutions with fossil/mineral CO_2** unattractive if it is not certain that the subsequent conversion of the CCU facilities to atmospheric/biogenic CO_2, or the conversion of the facilities that produce CO_2 (e.g. cement works, waste incinerators), to CCS is possible at acceptable costs. For CCU products such as synthetic aviation fuels, for which CCS is not possible, the use of fossil/mineral CO_2 would have to be offset by negative emissions in the long term.

In principle, measures should be taken that, primarily, avoid generating CO_2. CCU with fossil/mineral CO_2 must not lead to **lock-in effects**, which would be the case if using this CO_2 had the result that utilising fossil/mineral raw materials were to become more economically attractive and, as a result, be retained as the preference. European legislators have taken this into account with the provisions in RED II for the production of synthetic fuels recognised as renewable (these are known as "Renewable Fuels of Non-Biological Origin", or "RFNBO") (see Section 5.1).

In the long term, fossil/mineral CO_2 can only be used **in combination with CCS or CDR –** in a carbon-neutral system, any fossil/mineral CO_2 added must be offset by the removal and permanent storage of the same amount of CO_2. For example, the more fossil/mineral CO_2 is used for manufacturing plastics or kerosene, the more CCS and/or CDR is required in the overall system. It is irrelevant whether fossil/mineral, biogenic or atmospheric CO_2 is stored geologically, as long as the overall balance is even. Various possible scenarios should be compared in terms of energy input, costs and infrastructure requirements. The risks and environmental impacts of geological CO_2 storage must also be taken into account. Scientific studies on these aspects are available [42], but the decision is ultimately a socio-political one.

4.4 How are CCU and CCS related?

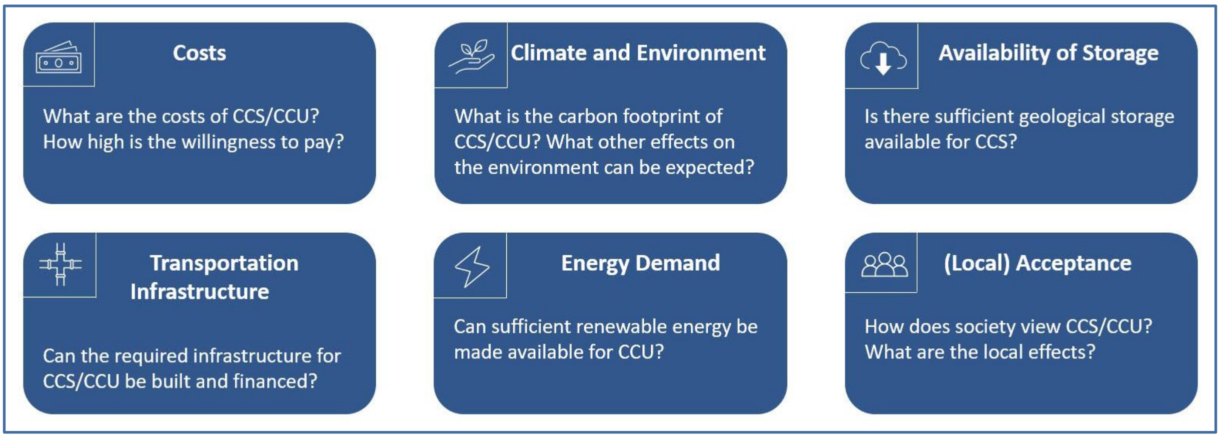
In a carbon-neutral economy, CCU and CCS have **different functions**. CCS aims to permanently sequester or remove CO_2 from the atmosphere. CCU primarily serves to develop a non-fossil carbon source. As CCU does not lead to permanent CO_2 storage in many cases, rather it merely delays its release into the atmosphere by a few weeks to a few years, CCU's contribution to climate change mitigation is based more on replacing fossil raw materials than on CO_2 storage. Consequently, CCU and CCS are not alternatives to each other, rather they complement each other.

In the medium term, it is to be expected that the tendency will be to store the **difficult-to-avoid CO_2** from fossil/mineral sources (CCS) rather than processing them further (CCU), due to the lower costs. CCU will only play a role in the long term (after 2030) in meeting the chemical industry's carbon demand. According to the experts interviewed by ESYS, CCU will also remain **more expensive** than CCS in the long term due to the high energy demand for hydrogen production.

An additional complication for the near-term market ramp-up is that the current framework conditions for CCU with short-lived products are unfavourable – for example, it is more profitable for cement works to dispose of the CO_2 with CCS because it would then not be subject to the European Emissions Trading System (EU-ETS). In the long term, it is conceivable that there will also be a higher willingness to pay for the long-term storage (BECCS, DACCS) of **atmospheric/biogenic CO_2** and, in turn, negative emissions than for the use of CO_2 as a carbon source. This will depend on the regulatory design of the incentives for negative emissions. In scenario studies for a carbon-neutral Germany, BECCS and DACCS play an important role in offsetting residual emissions. Furthermore, net negative emissions must be achieved after 2045. For companies that want to process CO_2, the **availability of CO_2 on the market** can present a hurdle if potential CO_2 suppliers focus exclusively on CCS and the transportation infrastructure is developed primarily with CCS in mind.

If the market ramp-up of CCU is to be made possible, the regulatory framework would have to take this potential utilization conflict into account and, if necessary, take countermeasures that favour CCU. This means that **regulatory incentives** will be needed for CCU, over and above the CO_2 price, if it is to prevail over the continued use of fossil carbon sources in conjunction with CCS (see Section 5.1).

Whether such a regulatory preference for CCU over CCS is desirable is a **social and political consideration** that depends on the factors shown in Figure 7. A comprehensive multi-criteria evaluation of scenarios with different weightings of CCU and CCS could provide a scientific basis for decision-making. **Further research** is needed here.



Costs

What are the costs of CCS/CCU? How high is the willingness to pay?

Climate and Environment

What is the carbon footprint of CCS/CCU? What other effects on the environment can be expected?

Availability of Storage

Is there sufficient geological storage available for CCS?

Transportation Infrastructure

Can the required infrastructure for CCS/CCU be built and financed?

Energy Demand

Can sufficient renewable energy be made available for CCU?

(Local) Acceptance

How does society view CCS/CCU? What are the local effects?

Figure 7: Factors to be considered when weighing CCS up against CCU. Source: authors' own work.

Synergy effects arise in case of a transition from CCS to CCU at a later date, as the same technologies and infrastructure are required for capturing and transporting CO_2. The transportation infrastructure required can also have an impact on the trade-off between CCS and CCU – CO_2 pipelines for transportation to geological storage sites will tend to be worthwhile for larger CO_2 sources only. CCU, on the other hand, could be more suitable for smaller quantities of CO_2, provided that the CO_2 can be processed in the immediate vicinity.

CCS has so far been viewed rather sceptically by the public, while CCU is still relatively unknown. The different functions should, therefore, be emphasised in **communications concerning carbon management**. CCU should not be presented as a way to "get rid of" CO_2 of fossil/mineral origin without the need for CCS. As explained in Section 4.2, CCU with fossil/mineral CO_2 is not carbon neutral in most cases. Furthermore, the high energy demand for CCU should be clarified. Under no circumstances should the impression arise that the production of fossil/mineral CO_2 is without its problems because it can be used to manufacture products with CCU.

5 Political and regulatory implementation: Enabling the market ramp-up for CCU, ensuring the contribution to climate change mitigation

5.1 What framework conditions would be required for CCU?

There are **central structural requirements** for the ramp-up of CCU in Germany. In addition to the availability of low-cost renewable energies, the creation of a **CO_2 infrastructure** is crucial (also for CCS). Indeed, the focus of the discussion is currently on the construction of dedicated CO_2 pipelines, although CO_2 can also be transported by ship or lorry. One question that remains unanswered is how CO_2 pipelines will be financed– state involvement could cushion the economic risks for private sector stakeholders and may be a necessary condition for ramping-up a CO_2 network. It is also unclear which companies will be connected to a future CO_2 pipeline. The public sector could play a coordinating role here.

In addition, there are a number of **regulatory aspects** that could complicate or additionally incentivise the ramp-up of CCU. In general, the experts interviewed by ESYS criticise the lack of coherence in the legislation in view of the large number of regulations affecting CCU (e.g. EU-ETS, EU-ETS 2, RED II, Union Certification Framework for Carbon Removals [CRCF Regulation]). This concerns, among other things, the question of how CCU's **impact on the climate** is recorded and priced, for example with regard to the period over which CO_2 must be stored in a product in order for it to be considered permanently sequestered (see Section 5.2). This has an impact on the economic viability of CCU processes.

According to some company representatives interviewed by ESYS, **fossil/mineral CO_2** use is necessary to ramp up CCU. One question that remains unanswered is how a reasonable transition period can be defined. To prevent fossil lock-ins, clear rules for the use of fossil/mineral CO_2 should be established at an early stage (see Section 4.3). European Union legislators are taking this into account in RED II via the RFNBO regulations – CO_2 from EU-ETS installations that require certificates can be used for their production, provided that certificates have been submitted. However, this is subject to a time limit of 2035 (for CO_2 from the electricity sector) or 2040 (for CO_2 from other sectors). Assuming that CCU will be available from 2030, this results in a time frame of 5 to 10 years. According to the company representatives interviewed by ESYS, this transitional solution provided for in RED II cannot be implemented in an economically viable manner, meaning that it does not contribute to the market ramp-up of CCU.

Market pull mechanisms could create **further economic incentives** for using CCU by incentivising demand for certain products. For example, the regulations for carbon-neutral aviation (ReFuelEU Aviation) and maritime (FuelEU Maritime) fuels create incentives for investing in CCU processes. Additional green lead markets, for example for carbon-neutral bulk chemicals, could create further incentives for CCU. Since chemical products are rarely directly demanded by the public sector, public procurement could only stimulate demand for CCU products to a limited extent. Minimum quotas for carbon-neutral bulk chemicals that distributors of these materials would have to fulfil could prove more effective. This could be anchored at EU level via the Ecodesign Regulation. [43] If green lead markets for chemical products are established, it must be clarified whether these only cover CCU products or other carbon-neutral products as well. A design that creates incentives for all carbon-neutral products and, in turn, establishes a level playing field seems sensible. In addition, funding (based on CapEx and OpEx) could support first movers in building CCU capacities in Germany. The experts interviewed by ESYS assessed the various options for creating economic incentives differently. This means that there is still a need for discussion and research to evaluate the instruments.

5.2 How can regulators record and price CCU's carbon footprint?

In order to set the appropriate economic incentives for transforming the industry by means of regulatory frameworks, the carbon footprint of individual CCU products and process chains must be recorded and verified. In doing this, it is important to **avoid excessive technical and administrative effort**.

Currently, there is a patchwork of sector and product-specific regulations, including the EU-ETS, the planned EU-ETS 2 and the requirements for RFNBO and Recycled Carbon Fuels (RCF) pursuant to RED II. This sometimes leads to **inconsistencies in how the carbon footprint is regulated**. The current framework penalises the manufacture of CCU products with non-permanent carbon sequestration from fossil/mineral CO_2 when compared to the manufacture of products made using fossil raw materials. This is because the CO_2 in the former case is subject to EU-ETS certification, whereas the use of fossil feedstocks is not. The proposed expansion of the EU-ETS to include waste incinerators could counteract this. However, in this case, it would be necessary to counteract the possibility of double pricing – for example, CO_2 from cement works used to manufacture CCU products with non-permanent carbon sequestration, which later end up in waste incineration, would be priced at both the cement works and the waste incinerator. This example shows that a consistent regulatory treatment of different CCU approaches, other carbon management approaches (CCS and CDR), the use of fossil feedstocks and circular economy approaches (e.g. chemical recycling) based on their impact on the climate is anything but trivial.

An important aspect when calculating the carbon footprint is the **storage period**. EU framework takes two different approaches here:

- The CRCF Regulation specifies a storage period of **35 years** – if biogenic or atmospheric CO_2 remains stored within a product for this period, it can be certified for negative emissions.
- With the 2021 revision of the EU-ETS, alongside CCS processes, CCU processes are also exempt from the requirement to obtain certificates under certain conditions. However, under the EU-ETS, the CO_2 must be bound "for a period of **at least several centuries**". According to the regulation, only mineral carbonates used in construction products fulfil this condition. [44] Recirculation of captured and reused CO_2 from high-temperature combustion (e.g. from waste incinerators) is explicitly excluded. [45] The EU-ETS equates permanent storage in products with geological storage, meaning that the processed CO_2 is not subject to certification. CO_2 that is not permanently stored, for example in the manufacture of CCU products with short useful lives, is subject to certification and is therefore considered equivalent to the immediate emission of the CO_2.

Many of the experts interviewed by ESYS believe that the EU-ETS regulation falls short. As previously explained, continuous recycling of products containing carbon or CCS during thermal recycling at the end of the respective product's useful life could also lead to a neutral carbon footprint. Therefore, it is not so much the individual product that matters as the **carbon flows in the overall system**. Future regulations should aim for a more differentiated and consistent assessment, and recognition of the impact on the climate, depending on the duration of storage. In this respect, the EU's plans to develop rules for dealing with CCU products with non-permanent carbon sequestration as part of the EU-ETS review planned for 2026 is to be welcomed. [46]

In addition to the storage period, the question of how the **origin of the carbon** can be traced through value chains and product life cycles is also crucial for determining the carbon footprint. Tracing CO_2 through the complex value chains in the chemical industry to the end of individual CCU products' useful lives, with possible subsequent recycling steps, is costly and time-consuming. One challenge here is that increasingly mixed flows of fossil/mineral and atmospheric/biogenic carbon will occur, for example in waste incineration (biogenic products, CCU products and plastics from fossil raw materials) and in chemical industry facilities that process mixed feedstocks (e.g. steam crackers, synthesis gas plants). Proof of origin would be a possible regulatory approach here. This is why the experts interviewed by ESYS believe that, in the long term, a regulatory system at EU level, in which the origin of the carbon does not have to be traced through the entire value chain, is desirable.

Ideally, a **uniform CO_2 pricing system** should be applied consistently to all carbon management activities, i.e. CCU, CCS and CDR. Two approaches in particular are being discussed for this purpose, both of which constitute a “in-out approach” in relation to the overall system and therefore do not require the CO_2 to be tracked through the process chains [4]:

- An “upstream pricing system”, in which pricing is based not on emissions but on where fossil raw materials are placed on the market, as is the case today in the German Fuel Emissions Trading Act (BEHG). In such an approach, when remunerating CO_2 removal, a distinction would have to be made with regard to the sequestration period.
- A “closed downstream pricing system” that prices all CO_2 emissions, regardless of the source of the carbon, and remunerates all removals, regardless of the use of the CO_2 and the sequestration period.

Both approaches would have to be developed in detail and checked for consistency, administrative effort, overlaps with other relevant regulations and effects on competition. The treatment of imported or exported products containing carbon and the associated potential for carbon leakage abroad would also need to be examined.

6 Conclusion

Many products containing carbon, which today are largely based on fossil raw materials, will also be required in a carbon-neutral future. This will necessitate the use of carbon sources that are neutral in terms of their impact on the climate. It is estimated that biomass and recycling alone will probably not suffice to meet future carbon demand. Based on what we know today, therefore, the use of CO_2 as a carbon source is **a necessary building block** for achieving carbon neutrality.

Although CCU only plays a role well beyond 2030 in scenario studies, the **course for this must be set in the next few years**. Indeed, many of the required technologies still need research and development, the infrastructure for the transportation of CO_2 must be built and a suitable regulatory framework for the market ramp-up must be created.

However, **excessively high expectations** should not be placed on CCU. Experts consider the availability of hydrogen, which is needed for the majority of CCU products, and, in turn, the availability of green electricity for its production, to be a bottleneck for the medium-term market ramp-up of CCU. Due to the high energy demand, in the long term, CCU is also likely to remain a very expensive climate change mitigation option. Providing sufficient quantities of feedstocks for the chemical industry and synthetic fuels for aviation and maritime transport in a carbon-neutral manner already constitutes a major challenge. Furthermore, there will be little scope for providing large quantities of hydrocarbons produced using CCU for other applications (such as road transport fuels). CCU is therefore not an alternative to reducing the demand for hydrocarbons, for example through the direct use of electricity, recycling and more frugal use of products containing carbon.

The **impact of CCU on the climate** is complex. Indeed, it depends on the CO_2 source used, the duration of the product's useful life, the destination of the CO_2 at the end of that product's useful life, the residual emissions due to incomplete CO_2 capture, the GHG emissions (in particular from the energy input) in the manufacture of the product from CO_2, the emissions from the construction of the CCU facilities and infrastructure, and the GHG emissions in the conventional processes that this approach substitutes. By replacing fossil raw materials, CCU can contribute to climate change mitigation. However, if CO_2 of fossil/mineral origin is used, it is generally not carbon neutral. Only in the case of goods with a very long useful life (e.g. building materials) is the CO_2 stored over a very long period, meaning that the climate change mitigation effect is comparable to CCS. In most cases, however, CCU only delays the release of CO_2 by the useful life of the product, which can range from a few days to several years. As a result, atmospheric/biogenic CO_2 usually has to be used as a carbon source to ensure that the CCU process is carbon-neutral. Closed recycling loops can keep CO_2 out of the atmosphere for a longer period of time, even for products with a short useful life. When using fossil/mineral CO_2, it would be necessary to ensure that the CO_2 is captured and stored permanently using CCS at the end of the product's useful life (e.g. during waste incineration), or that the emissions are offset by negative emissions (e.g. DACCS). To make the best possible use of CCU for industrial transformation, the impact of various CCU applications on the climate must be assessed and priced consistently and on a differentiated basis. How this can be achieved with limited administrative effort is an unanswered question that science and politics should address urgently (see areas of conflict in Figure 8).

Under the current framework, there are **few incentives for companies** to develop CCU value chains. An appropriate regulatory framework must therefore be created to ensure that the necessary CCU market ramp-up occurs in time to meet the climate targets. In this context, a balance must be struck between the risk of rendering the introduction of CCU unattractive by placing excessive demands on the carbon footprint and thereby slowing down the necessary development, and the risk of promoting CCU pathways that ultimately do not lead to carbon neutrality and, in the worst case, extend the use of fossil raw materials (see areas of conflict in Figure 8). By 2045 (in Germany) or 2050 (in the rest of the EU) at the latest, processes would have to be adapted to use atmospheric or biogenic CO_2. If we are to become carbon-neutral and still continue to use hard-to-abate CO_2 from fossil/mineral sources, we must ensure that the CO_2 is captured using CCS at the end of the product's useful life (e.g. during waste incineration) or that the emissions are offset by negative emissions. This means that there is only a **short window of opportunity** to implement non-carbon-neutral transitional solutions and the opportunities and risks of such transitional solutions should be analysed in more detail. This includes considering the extent to which the continued use of fossil carbon sources in conjunction with CCS should be permitted as an alternative to CCU.

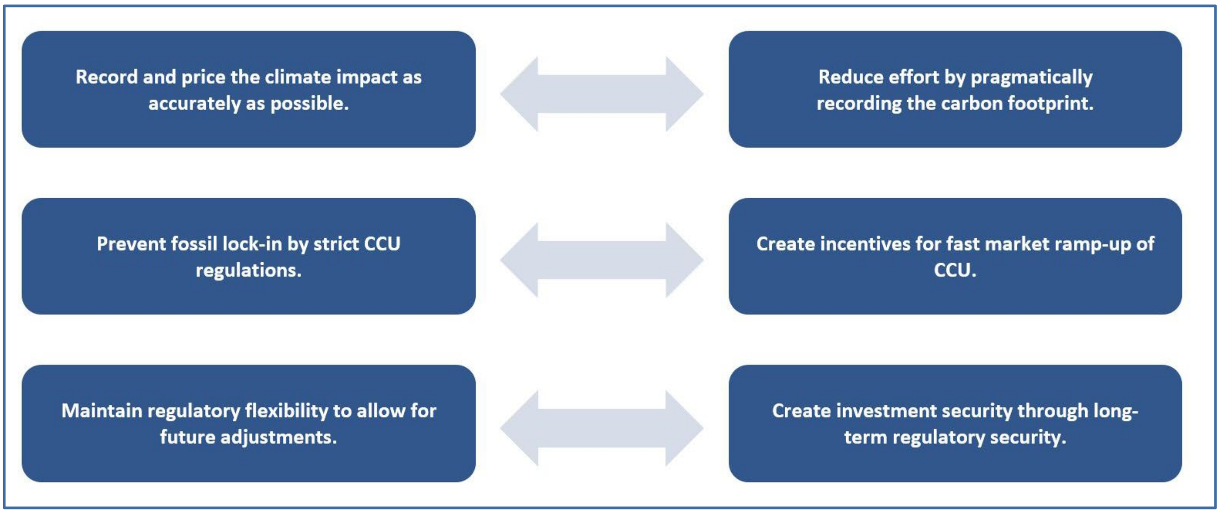


Figure 8: A regulatory framework for CCU must navigate several areas of conflict, some of which are difficult to reconcile. Source: authors' own work.

In addition, numerous **interfaces to other strategies and subsystems** must be taken into account and regulated. Above all, it is crucial that CCU be incorporated into a comprehensive **carbon management strategy** to ensure consistent regulation of CCU, CCS and CDR. Such a strategy is also crucial for estimating the need for CO_2 transportation as a basis for developing the transportation infrastructure. The integration of CCU into the **circular economy strategy** is also particularly crucial for plastics. Interfaces with the energy system development especially arise from CCU's high energy requirements, which must be taken into account in the expansion targets for renewable energies. The demand for synthetic fuels produced by CCU depends on which areas of the energy system can be supplied with electricity and to what extent energy demand can be reduced by increasing energy efficiency. There is another important interface with the **biomass strategy** – the more biomass can be diverted from energy use and channelled into use as a feedstock, the lower the demand for CCU.

When regulating CCU and developing CCU value chains, it is important to adopt a **global perspective**. This is because the limited availability of hydrogen with low greenhouse gas emissions and carbon-neutral energy in Germany means that feedstocks and synthetic fuels manufactured using CCU will probably have to be imported, possibly to a large extent from outside the EU. Many chemical products are globally traded commodities. Especially for Germany, with its extensive chemical industry, shaping the upcoming **feedstock change** towards carbon-neutral closed cycles will require a profound transformation that should be planned via a **forward-looking industrial strategy** – not least with regard to which parts of the value chains are kept within Germany. A CBAM and other protective mechanisms also have an important role to play here with a view to preventing competitive disadvantages for European industry compared to suppliers from third countries with less stringent climate change mitigation ambitions.

CCU is still relatively unknown among the general public. It is therefore the responsibility of the scientific, political and industrial communities to communicate the importance of feedstock change in the chemical industry for achieving carbon neutrality, as well as the role of CCU in this transformation. It is important to clarify the **different ways in which CCU, CCS and CDR each contribute to climate change mitigation** – CCS prevents hard-to-abate CO_2 from industrial processes from entering the atmosphere. If CCS is used to store atmospheric/biogenic CO_2 it is considered to be CDR and leads to negative emissions. In addition to the CDR methods BECCS and DACCS, which use CCS, there are also other techniques in which carbon is stored (e.g. afforestation). Both CCS and CDR aim to store CO_2 permanently. CCU, on the other hand, taps an alternative carbon source to replace fossil raw materials. It only offers a permanent solution for dealing with hard-to-abate CO_2 originating from fossil/mineral sources if products with very long useful lives are manufactured, in permanent recycling or in combination with CCS at the end of the CCU product’s useful life – and therefore only in certain applications. CCU can result in negative emissions if atmospheric or biogenic CO_2 is used in the applications mentioned above. Meeting long-term climate targets requires the interplay of all three carbon management approaches. CCU can only supplement CCS and CDR, not replace them.

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