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Part 1: Basic elements for avoiding greenhouse gases and generating climate-neutral energy (technical toolbox)

Chapter 2-9

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2.9 Carbon Capture and Usage (CCU

2.9.1 Introduction

Climate change presents us with the challenge of drastically reducing CO_2 emissions and finding new ways to deal with the remaining emissions. One important possibility is to capture CO_2 from exhaust gases, e.g. from power plants or from industrial processes (e.g. the cement industry). This is referred to as "carbon capture" (CC). CO_2 can also be filtered directly from the atmosphere – albeit at significantly higher energy and cost expenditures ("Direct Air Capture" or DAC). This report deals in detail with the different processes and their advantages and disadvantages in the previous chapter 2.8.

There are essentially two ways to deal with captured CO_2. Carbon capture and storage (CCS) involves permanently injecting the CO_2, e.g. into geological formations deep in the ground. This report also deals with this in chapter 2.8. Another possibility is to put the CO_2 to further use, either in a carbon cycle or product-bound. The term "carbon capture and utilisation" (CCU) is often used as an umbrella term for this. In its Sixth Assessment Report, published in 2022, the Intergovernmental Panel on Climate Change identifies carbon capture and utilisation for the first time as a suitable solution for mitigating climate change.[447] Several future scenarios for net zero in the chemical industry by 2050 continue to show that between 10 – 30 % of the demand of product-bound carbon could come from the use of CO_2.[448]

Today, the so-called "Enhanced Oil / Gas Recovery (EOR / EGR)" is still the most important form of utilisation of CO_2. In EOR, for example, CO_2 is injected into active oil reservoirs to produce more oil. Another very significant potential use of CO_2 is the production of synthetic fuels. This component, which is essential for climate neutrality in the mobility sector, is described in detail in Chapter 2.7 of this report. However, CO_2 can also be converted into products of the chemical industry such as methanol, urea or plastics. In this context, the use of CO_2 can not only contribute to reducing dependence on fossil fuels, but also create new markets and technologies.

This is important from the perspective of the chemical industry, which is responsible for considerable amounts of CO_2 emissions. These are largely caused by the use of fossil fuels, which is necessary for the process heat required for many chemical reactions. The use of an increasing share of renewable energies can contribute to making the energy supply more climate-neutral. In chemical value creation, however, carbon will continue to be needed for most products. In addition to energy supply, it must therefore be a goal to make chemical production

[447]Cf. (IPCC, 2022)
[448]Cf. (Kähler, 2023).

independent of fossil carbon. CO_2 of all things can provide a remedy here. It can replace fossil raw materials such as oil and gas and thus enable the entry into the circular economy of CO_2. This could, for example, reduce the CO_2 footprint of the chemical industry and find another customer for the use of CO_2 previously removed from the atmosphere. Dr Helmut Leibinger, Head of Plant and Process Engineering at Rohrdorfer Zement, says: "With CO_2 as a carbon source, Germany can protect the climate and at the same time become less dependent on oil and natural gas. In addition, value creation and thus jobs remain in the country".[449] However, new process flows are usually required in order to use CO_2 as a chemical "building block".

Alternatively, this task can be performed by microorganisms, for example. Consequently, this chapter also deals with the production of biomass using previously captured CO_2 . Finally, the so-called mineralisation or carbonation of CO_2 is described. The products generated by the latter can serve the construction industry, for example, and reduce its CO_2 footprint.

Figure 177 gives a good overview of the different uses of CO_2 . It can serve as an introduction to the topic, although this chapter only covers selected pathways.

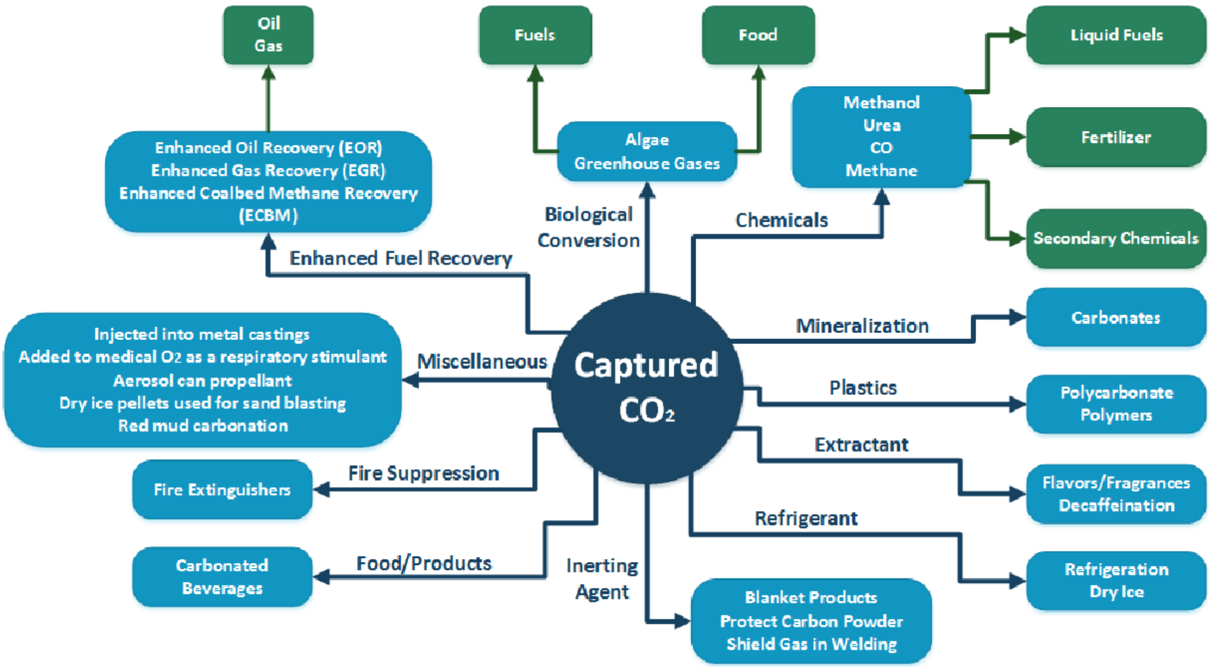

Figure 177: Overview of the different uses of captured CO_2 (CCU)

Source: R. Debek, "Catalysts for Chemical CO2 Utilization", Thesis, Sorbonne Univ. , 2016

[449] Cf. (Ingenieur.de, 2022)

2.9.2 CO_2-Use in the chemical industry

The chemical industry is responsible for about 12 % of CO_2 emissions worldwide.[450] About 30 % of the CO_2 footprint of products comes from the energy used, 70 % from the raw materials used.[451] In order to improve the carbon footprint of the chemical industry, the use of CO_2 as a raw material substitute is becoming increasingly important.[452] It is both a promising approach to reduce CO_2 emissions and to promote sustainability in the sense of a CO_2 circular economy. The conversion of CO_2 into valuable chemicals, plastics and materials also offers the potential to reduce dependence on fossil carbon sources, as to date around 90 % of the feedstock for chemical products comes from fossil sources such as oil, coal or natural gas.[453] CO_2 can be used, for example, in the production of plastics, fertilisers and fuels (for fuels see chapter 2.7). Here, the gas can be used either directly as a raw material or as a starting material for the synthesis of other products. An example of this is the use of CO_2 as a feedstock for the production of methanol. Here, the CO_2 is reacted with hydrogen to form methanol. Another possibility is to use CO_2 as a starting material for the production of polyols, which can be used in the production of polyurethanes. CO_2 emissions from the use of fossil energy can be reduced, among other things, through electrification of processes – wherever possible – and process improvements.

2.9.2.1 Use of CO_2 for the production of chemical raw materials

Carbon dioxide is not only a greenhouse gas and a waste product of fossil fuel combustion. It can also be a potential raw material for the chemical industry. CO_2 can, for example, be used as a feedstock for the production of chemicals such as methanol, formaldehyde and others.[454] The use of CO_2 as a raw material can thus help close the carbon cycle and reduce dependence on fossil fuels.[455] Using CO_2 as a raw material in the production of chemicals can make an important contribution to climate protection. This section presents various chemicals that can be produced from CO_2, including methanol, urea and synthesis gas.

[450] Cf. (Federal Office, 2023).
[451] Cf. (BASF, BASF, 2023)
[452] Cf. (Handelsblatt, 2021)
[453] Cf. (BMBF, 2023)
[454] Cf. (Handelsblatt, 2021)
[455] Cf. (BMBF, 2023) https://www.bmbf.de/bmbf/de/forschung/umwelt-und-klima/ressourcen/kohlendioxid-als-rohstoff.html

2.9.2.2 Methanol

Methanol production is a large-scale process and methanol (CH_3OH) is today mainly produced from synthesis gas. Synthesis gas is obtained by steam reforming or the partial oxidation of natural gas and the gasification of coal,[456] whereby natural gas is mostly used as a raw material in North America and Europe, and coal in China. Methanol is used as a solvent, fuel and precursor for a variety of chemicals. With global methanol production expected to reach about 110 million tonnes by 2020, there is a large demand for fossil raw materials.[457] The synthesis of methanol from captured CO_2 thus represents an interesting possibility for using the greenhouse gas CO_2 as a raw material.

The synthesis of methanol from CO_2 is carried out either by direct catalytic reaction with hydrogen (preferably produced with a low level of CO_2) or – for reasons of efficiency – in two stages by catalytic conversion of the CO_2 into CO ("Reverse Water Gas Shift", RWGS) and subsequent catalytic reaction with hydrogen.

The synthesis of methanol from captured CO_2 offers several advantages. On the one hand, methanol can be used as a renewable fuel and thus contribute to reducing the demand for energy sources. On the other hand, methanol based on CO_2 can partially replace fossil carbon as a raw material for the chemical industry and close the CO_2 cycle or, in some cases, also act as a CO_2 sink.[458]

2.9.2.3 Methane

The synthesis of methane from captured CO_2, also known as the power-to-gas process, is a promising method for converting carbon dioxide into a valuable and renewable gas. Methane synthesis can be achieved by several processes, including thermal methanation, catalytic methanation and biological methanation. In this chapter, we will focus on catalytic methanation.

Catalytic methanation is a process in which CO_2 and hydrogen (H_2) and are converted to methane (CH_4) using a catalyst, preferably the hydrogen is obtained by the electrolysis of water and the CO_2 is captured either from industrial waste gases or from the atmosphere or comes from biomass. The reaction proceeds according to the following reaction equation:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O, \quad \Delta H = -165\ kJ/mol$$

This reaction is strongly exothermic. The reaction conditions, such as the pressure and temperature, influence the yield and selectivity of the process. Typically, the process is carried out

[456] Cf. (Chemie.de, 2023)
[457] Cf. (Mordor Intelligence, 2023)
[458] Cf. (Biomasse-Nutzung.de, 2023)

at high temperatures (300 – 500 °C) and pressures (10 – 30 bar). It is therefore crucial that the energy required for this is provided in a climate-neutral way.

Similar to methanol synthesis from CO_2, the choice of catalyst is an important factor in catalytic methanation, especially with regard to its coking resistance and service life.

Catalytic methanation has the potential to make an important contribution to the decarbonisation of industry and the energy sector. Methane is a versatile fuel that can be used in industry, transportation and power generation. In addition, methane synthesis can serve as a method for seasonal storage of renewable energy by converting excess electricity from renewable sources into hydrogen and then synthesising it into methane.

2.9.2.4 Urea

Urea is an important nitrogen fertiliser used in large quantities in agriculture. Conventionally, urea is produced using ammonia from natural gas and carbon dioxide (also from natural gas) through urea synthesis. From a climate protection point of view, the aim should be to produce ammonia from atmospheric nitrogen and electrolysis hydrogen. In this case, of course, the carbon dioxide from the natural gas is no longer available and can be replaced by previously captured carbon dioxide.

shows that today the use of CO_2 for urea synthesis accounts for around 57 % of total CO_2 consumption.

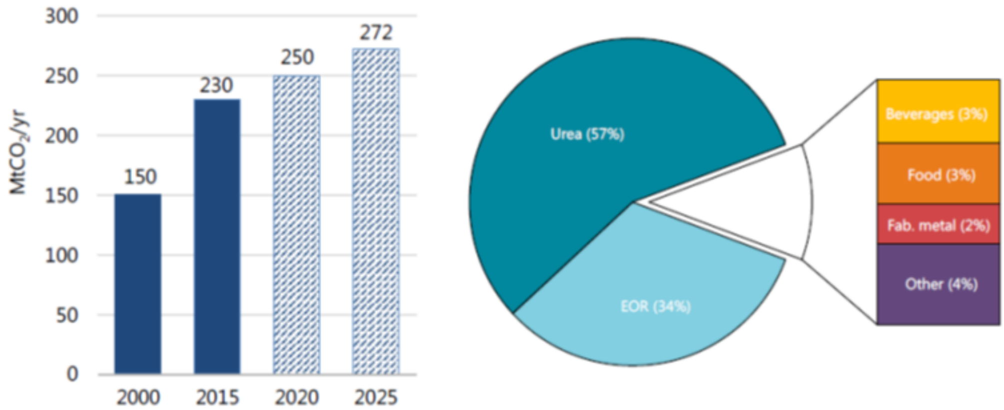

Figure 178: Global consumption of CO_2

Source: Analyis based on ETC (2018), Carbon Capture in a Zero-Carbon Economy ; IHS Market (2018), Chemical Economics Handbook - Carbon Dioxide; US EPA (2018), Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990 - 2016.

The synthesis of urea is carried out by a reaction of ammonia and CO_2 via the intermediate stage ammonium carbamate. The chemical formula for the synthesis of urea from CO_2 is:

$$CO_2 + 2\ NH_3 \rightarrow CO(NH_2)_2 + H_2O$$

It is therefore one of the few "CO_2 -consuming" chemical reactions. Urea can then be used for a variety of applications, especially in fertilisers, as a component of urea resins or as a starting material for the synthesis of other chemical compounds. Around 185,000 tonnes of urea are currently produced annually worldwide.

2.9.2.5 Synthesis gas

Synthesis gas, a mixture of carbon monoxide and hydrogen, is one of the most important building blocks for the production of chemicals and fuels. Current syngas production relies on fossil fuels, such as coal and natural gas. If an alternative source of hydrogen is available, captured CO_2 can be used to produce CO either directly or via the RWGS intermediate step (see above). This opens up various alternatives to close the carbon cycle and reduce the carbon footprint.

An effective method for producing synthesis gas from CO_2 is the so-called dry reforming of methane with CO_2. The reaction takes place at high temperatures and pressures and is supported by a catalyst to achieve a higher yield. To reduce the dependence on fossil methane, biogas obtained from organic waste can serve as a source of methane for this pathway. Reforming biogas with CO_2 can produce synthesis gas, which can serve as a renewable raw material for the chemical industry.

However, further research is needed to improve the efficiency and cost-effectiveness of these processes.

2.9.3 Use of CO_2 for the production of plastics and polymers

The use of CO_2 as a raw material for the production of plastics and polymers is a promising approach with regard to the reduction of CO_2 emissions and the use of waste products. The greenhouse gas CO_2 is used as a valuable raw material for the production of plastics instead of being disposed of as a waste product. For example, the increasing demand for sustainable materials has led to an interest in using carbon dioxide as a feedstock for the production of polymers.[459] CO_2 can be used as a building block in the production of polycarbonates and polyurethanes, which have multiple applications in the automotive, electronics and construction industries. The use of CO_2 as a component for polymer production can thus help to bind CO_2 and promote its use.

[459] Cf. (Nova Institute , 2023)

In this chapter, various processes for the production of plastics and polymers from CO_2 are presented and their potential for sustainable and environmentally friendly production is discussed.

2.9.3.1 Polycarbonate

A special application of CO_2 in the chemical industry is the production of polycarbonates. Polycarbonates are thermoplastic polymers known for their excellent combination of transparency, hardness and impact resistance. They are used in many areas, such as electronics, the automotive industry, medical technology and the construction industry. Currently, polycarbonates are made from fossil-based raw materials that contribute to greenhouse gas emissions. The most commonly used building block for polycarbonates is bisphenol A (BPA), which is derived from fossil fuels. It is also suspected of being harmful to health. Alternatively, CO_2 can be used as a building block in the production of polycarbonates, replacing BPA. The most commonly used synthesis method for CO_2-based polycarbonates is the reaction between CO_2 and epoxides. The reaction is catalysed by metal complexes or organic bases and produces cyclic carbonates which are then polymerised to form polycarbonates.

The first synthesis of polycarbonates from CO_2 was carried out in the 1960s. Since then, many researchers and companies have pursued the development of efficient and selective catalysts to improve the conversion of CO_2 and epoxides). In recent years, several advanced catalysts have been developed that exhibit high activity and selectivity for the synthesis of polycarbonates from CO_2.

The use of captured CO_2 for polycarbonate production has several advantages. First, it partially replaces fossil-based components. Secondly, it reduces greenhouse gas emissions by using CO_2 as a raw material instead of releasing it into the atmosphere.

However, the production of polycarbonates from captured CO_2 is not without challenges. One important challenge is the limited availability of CO_2 sources and the difficulty of obtaining CO_2 in sufficient purity and quantity. Another problem is the high energy intensity of synthesising polycarbonates from CO_2. It must of course be possible to provide this energy in a climate-neutral way in order to make the overall process meaningful from an environmental perspective.

2.9.3.2 Polyols / Polyurethanes

Polyols are a group of chemical compounds containing multiple hydroxyl groups (-OH), while polyurethanes are synthetic polymers produced by reacting polyols with diisocyanates. Polyols are used as raw materials in the production of polyurethanes. The hydroxyl groups of the polyols react with the isocyanate groups of the diisocyanates to form polyurethane polymers. Polyurethanes are used in a variety of applications, e.g. as insulating materials, coatings, adhesives, foams and elastomers.

A promising approach to the production of polyurethanes from captured CO_2 is the use of CO_2 polyols. These polyols are produced by reacting epoxides with CO_2 and can be used as part of polyurethane production. By using CO_2 polyols, the amount of fossil raw materials in polyurethanes can be reduced, which contributes to a reduction in CO_2 emissions and reduces the dependence of the chemical plastics industry on fossil feedstocks.

The preparation of CO_2 polyols can be done in various ways, including the use of different epoxides such as propylene oxide, ethylene oxide and glycidyl methacrylate. The reaction of epoxides with CO_2 takes place in the presence of catalysts and co-catalysts such as amines and metal compounds.

Overall, the production of polyurethanes from captured CO_2 offers promising potential for reducing dependence on fossil fuels and lowering CO_2 emissions. However, further research is needed to improve the efficiency and cost-effectiveness of this technology.

Table 2 provides an overview of products made from CO_2 and their production capacities in 2022 and an outlook for 2023.[460]

[460] Cf. (Nova Institute , 2023)

Table 44: CO_2-based products, production capacities 2022 and outlook 2030. Modified according to a press release of the nova Institute of 17 April 2023.

Products	CO_2-based carbon content	Production capacity 2022	Outlook 2030
Novel CO_2 -based products - a total of 1.3 Mt/a in 2022, Outlook for more than 6 Mt/a in 2030			
Aromatic polycarbonate (PC)	5 %	900,500 t/a	1.2 Mt/a
Aliphatic polycarbonates (APC)	11 –12 %	120,000 t/a	300,000 t/a PPC, PEC
Methanol	100 %	approx. 115,000 t/a	1 Mt/a
Polyhydroxyalkanoates (PHA)	100 %	5,000 – 10,000 t/a	30,000 t/a
Methane	100 %	Several pilot plants	325,000 t/a

2.9.4 Examples of applications of CO_2 in the chemical industry

Covestro

The German company Covestro is a leading manufacturer of polymers and plastics. In a joint project with RWTH Aachen University, the group has developed a process with which CO_2 can be used as a raw material for the production of polyurethane foams. The CO_2 is converted in a chemical process with other raw materials to a polyol, which is then used in foam production. The products are added to Covestro's plastics and are already in commercial use: not only in sports flooring but also in foams for mattresses or shoe upholstery. In Covestro's first large-scale plant, about 5,000 t of polyol (enough for 500,000 mattresses) are produced annually with an annual added value of about € 75 million. In this first plant, 20 % of previously captured CO_2 is incorporated in the production process of the end products and, accordingly, 20 % less fossil raw material is required as a starting product. This is accompanied by a corresponding reduction in CO_2 along the entire value chain. With this process, Covestro sees itself at the forefront of a technology trend that could fundamentally change the production of plastics and chemicals. Until now, the industry has been getting the carbon it needs from oil and gas – combined with massive emissions. In the future, it will increasingly be obtained from CO_2.[461]

[461] Cf. (Covestro, no time stated)

Carbon Recycling International (CRI)

CRI is an Icelandic company that has been capturing CO_2 from the air or exhaust streams since 2006 and converting it into methanol that can serve as a fuel or feedstock for the chemical industry. The company uses renewable energy sources such as geothermal and hydroelectric power to run the CO_2 capture process. The necessary hydrogen is also produced with the help of renewable energies via water electrolysis. Alternatively, however, hydrogen from by-products or exhaust gases is also used. This then leads not to e-methanol, but low-carbon methanol. The capture of CO_2 emissions, their combination with green or recovered H_2 to produce methanol and their recycling into industrial processes as a renewable energy source and feedstock, offers an accelerated path to a circular economy.

In 2012, for example, CRI claimed to be the first company to produce renewable methanol on an industrial scale, and in 2022 the world's first production plant for methanol from recycled carbon with a capacity of 110 kt/a was commissioned.[462]

2.9.4.1 Potential advantages of using CO_2 as a raw material in the chemical industry

CO_2 can be used as a raw material in the chemical industry. Researchers are looking for suitable molecular catalysts and production processes to convert CO_2 into methanol and other chemical raw materials and materials.[463] These new products have an improved ecological balance and in some cases even better properties than their fossil predecessors.[464] Thus, the use of CO_2 as a raw material in the chemical industry has gained in importance in recent years, as it represents a promising way to reduce dependence on fossil raw materials and at the same time contribute to climate protection. Increasingly, industry and companies are also interested in CCU processes in this field.[465] The advantages are:

- **Reducing greenhouse gas emissions:** The use of CO_2 as a raw material in the chemical industry can help reduce greenhouse gas emissions by using it as a substitute for fossil raw materials. Using CO_2 as a raw material prevents it from escaping into the atmosphere, where it acts as a greenhouse gas.
- **Resource conservation:** The use of CO_2 as a raw material can also contribute to resource conservation. By using CO_2 as a raw material, fossil raw materials can be saved.

[462] Cf. (Carbon Recycling International, 2023)
[463] Cf. (Hergersberg, 2019)
[464] Cf. (BMBF, 2023)
[465] Cf. (Nova Institute , 2023)

- **Innovative products:** The use of CO_2 as a raw material can also help to develop innovative products. One example is polyurethanes that can be made from CO_2 and polyols. These polyurethanes have similar properties to conventional polyurethanes, but can be produced from sustainable raw materials.
- **Economic advantages:** The use of CO_2 as a raw material can also offer economic advantages. On the one hand, companies that use CO_2 as a raw material can become less dependent on rising raw material prices. On the other hand, companies that use CO_2 as a raw material can benefit from public funding programmes aimed at reducing greenhouse gas emissions. With increasing costs for CO_2 emissions, e.g. within the framework of the EU ETS, measures to save CO_2 will make more and more economic sense in the future.

2.9.5 Challenges in the implementation of CO_2 use in the chemical industry

One of the biggest challenges in using CO_2 as a feedstock in the chemical industry is the fact that the development of suitable catalysts and production processes.[466] According to Hepburn, the use of CO_2 in chemical reactions to build products such as methanol, urea or polymers could consume 0.3 – 0.6 Gt CO_2 annually by 2050. However, the costs he quotes between 80 – 300 USD/t CO_2 are partly higher than CO_2.[467] It is therefore important to reduce the cost side.

There are also comparatively few chemical processes in which carbon dioxide remains permanently bound.[468] The CO_2 bound in the products during the course of use is released again at the end of the product's life – as long as the CO_2 cycle is not yet completely closed.[469]

Moreover, "the use of CO_2 as a material cannot solve the climate problem", Carus clarifies in an article from 2012. For example, he states that if the EU chemical industry had used CO_2 as a carbon source instead of petroleum in 2009, it would have needed 233 Mt CO_2. This is just over 5% of the EU's total CO_2 emissions. "But that is at least twice as much as the chemical industry itself emits in CO_2," Carus adds. The chemical industry could therefore theoretically become a sink for the climate gas – if the required energy comes from renewable sources.[470] Only when basic chemical materials are increasingly produced from less fossil raw materials

466Cf. (Hergersberg, 2019)
467Cf. (Hepburn, 2019)
468 Cf. (German Bundestag - Scientific Services, 2009)
469 Cf. (BMWK, no time given)
470 Cf. (Ahrens, 2012).

will the demand for CO_2 as a raw material change significantly. However, it will also be important to provide the corresponding amounts of electricity from renewable sources.[471]

Despite these challenges, there are already a number of projects and research work looking at the use of CO_2 as a raw material in the chemical industry. The use of CO_2 as a raw material can help close the carbon cycle and reduce dependence on fossil fuels.[472]

2.9.6 Mineralisation of CO_2 for the extraction of carbonates and building materials

Carbonates are used in numerous industries, e.g. in the construction industry, as food additives, as fillers for paper and in the chemical industry. Huge quantities of natural limestone (calcium carbonate, $CaCO_3$) are converted, especially for infrastructure projects, to produce cement and ultimately concrete. During the calcination process required for this, large quantities of CO_2 escape (cf. chapter 3.2.2. of this report). It can be simplified as follows:

$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$

In opposite processes, however, the CO_2 can be used again to produce carbonates from it. "The so-called carbonation of hardened concrete, for example, is a naturally occurring chemical reaction in which CO_2 from the ambient air enters the concrete and reacts with the hydration products in the hardened cement paste".[473] The simplified chemical equation is given below:

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

The production of carbonates from carbon dioxide (CO_2) is also an important process in the chemical industry. One example is the production of calcium carbonate, which is used in many applications such as paper production, paints and varnishes, and as a filler in plastics.

The use of carbon dioxide as a raw material for the production of carbonates and building materials has recently become increasingly important. Its conversion is seen as a way to reduce emissions of CO_2 into the atmosphere and at the same time to obtain valuable products.

This chapter deals with the use of CO_2 in the production of carbonates and building materials. It deals with different technologies that enable the use of CO_2 in the production of e.g. concrete, bricks, sand-lime bricks and carbonates.

[471] Cf. (DECHEMA and FutureCamp for the VCI, 2020)
[472] Cf. (Hergersberg, 2019).
[473] Cf. (VDZ, 2020)

2.9.6.1 Carbonates

Carbonates are inorganic salts and organic esters of carbonic acid (H_2CO_3). The use of CO_2 for the production of artificial carbonates offers a promising alternative to the use of natural raw materials, e.g. limestone. There are various processes for the production of carbonates from CO_2. One process, for example, is the reaction of CO_2 with calcium hydroxide ($Ca(OH)_2$) to form calcium carbonate ($CaCO_3$). Another process is the reaction of CO_2 with sodium hydroxide (NaOH) to form sodium carbonate (Na_2CO_3).

Artificial carbonates produced from CO_2 can find application in various fields, such as building materials, as fillers for plastics or as catalysts in the chemical industry.

There are various methods for producing carbonates from CO_2, such as the so-called mineralisation process, in which CO_2 and water react with mineral raw materials such as silicates to form calcium carbonate ($CaCO_3$), for example. Another method is the carbonation of waste and by-products, where CO_2 is injected into waste such as fly ash, slag or other material to convert it into carbonates.

An example of a project that deals with the use of CO_2 as a raw material in the chemical industry is Carbon2Chem by thyssenkrupp. The project aims to transfer the metallurgical gas from steel production directly for use in chemical plants.[474]

2.9.6.2 Building materials

Concrete is the most widely used building material in the world and is used for a variety of applications such as foundations, retaining walls and road construction. However, the conventional production of concrete requires large quantities of cement, which is produced by burning limestone and contributes to the release of CO_2 into the atmosphere. For this reason, work has been going on for several years to develop processes for the production of concrete from CO_2 and the reuse (recycling) of concrete. The use of CO_2 in the production of building materials can help to reduce the carbon footprint of buildings and infrastructure and thus contribute to the achievement of climate targets.

As already mentioned in the introduction to this chapter, so-called recarbonatisation takes place on the surfaces of building materials made of cement or lime through the absorption of CO_2 from the air. It is estimated that between 1930 and 2013, 43 % of the worldwide CO_2 process emissions from cement production were reabsorbed through recarbonatisation.[475] If the CO_2 emissions of the fuels required in the process are also included, around 25 % of the

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[474] Cf. (Handelsblatt, 2021)
[475] Cf. (Xi & al., 2016)

original emissions were mathematically recaptured.[476] This natural reaction can be specifically accelerated and optimised by using high CO_2 concentrations and good reaction conditions.[477] "Alternatively, large surfaces are required, such as with processed old concrete". [478]

Consequently, in the CCU pathway of recarbonatisation or mineralisation (the recycling) of old building material, the crushing of the old concrete is essential to obtain the largest possible surface area. The ground old concrete is then mixed with captured CO_2, which does not give the concrete more strength, but an additional 30 % CO_2 is absorbed in a few hours instead of decades. [479]

A critical point to note here is that the additional energy required for the grinding and crushing process must be provided in a climate-neutral way in order not to worsen the CO_2 balance of concrete recycling again.

The potential for recarbonisation is otherwise huge. Construction waste, for example, represents the largest type of waste in Europe in terms of volume and accounts for about 30 % of landfills.[480] The first companies are already trying to realise this potential. The start-up Neustark AG, for example, has developed a pilot plant in which 100 kg CO_2 can be stored in the concrete granulate per hour. By comparison, fast-growing spruces or firs absorb about 20 kg CO_2 per year and tree. According to the company's information, one plant can achieve within one hour what five spruces need a whole year for.

However, space must be found for the preparation and storage of the construction waste. This preliminary process also requires time, energy and the corresponding legal framework conditions, so that it is still easier to produce new concrete than recycled concrete today, according to Peter Lukas from HeidelbergCement.

As an alternative to recycling old concrete through recarbonation with CO_2, the climate gas can also be used within the framework of so-called CO_2 mineralisation to form stable carbonate minerals from minerals or industrial waste. The resulting products are then to be utilised. The use of these products may mean that the CO_2 emission reductions can generate additional income instead of incurring costs.

These reactions result in long-term storage of CO_2. Early evidence suggests that the products can potentially be used in a range of applications in addition to CO_2 storage, including as fillers,

[476] Cf. (VDZ, 2020)
[477] Cf. (CO_2 Value Europe, 2020)
[478] Cf. (VDZ, 2020)
[479] Cf. (Joas, 2020)
[480] Cf. (Holcim, 2020)

polymer additives, land reclamation or as supplementary cementitious materials (SCMs), generating revenues of 14 – 700€/t of captured CO_2.[481]

Several feedstocks or raw materials for CO_2 mineralisation have been proposed, mainly natural rocks containing magnesium- or calcium-rich silicate minerals and alkaline industrial residues (e.g. steel slag or fly ash). While natural rocks are attractive because they are an abundant resource that could be used worldwide, industrial wastes are attractive because they are available in industrial regions and do not need to be mined.

To enable significant emission reductions through CO_2 mineralisation with a highly predictable feedstock, the focus is on using natural rock as a resource for CO_2 mineralisation. It is worth noting here that CCS uses similar principles by injecting CO_2 into basaltic rock layers. The CO_2 then mineralises and is thus permanently bound.

Examples of natural minerals are forsterite (Mg_2SiO_4), which occurs in olivine-bearing rocks, lizardite ($Mg_3Si_2O_5(OH)_4$) in serpentine-bearing rocks and wollastonite ($CaSiO_3$). The general CO_2 mineralisation reactions for these example minerals are as follows

$Mg_2SiO_4 + 2CO_2 \rightarrow 2\ MgCO_3 + SiO_2 + heat\uparrow$

$Mg_3Si_2O_5(OH)_4 + 3\ CO_2 \rightarrow 3\ MgCO_3 + 2\ SiO_2 + heat\uparrow$

$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2 + heat\uparrow$

The authors of an article published in Nature – Communications Earth & Environment in 2022 were able to show "that under the right circumstances, positive business cases exist when revenues can be generated by using mineralisation products as SCM".[482]

Finally, a project by the company Saudi Aramco should be mentioned in which a "sink" is to be created for previously captured CO_2 in the concrete without impairing or negatively influencing the strength of the end product. To achieve this, various concrete curing combinations with different CO_2 concentrations were tested. The key was the combination of CO_2 and steam, which resulted in a CO_2 uptake of 20 % in the concrete. The resulting concrete also showed improved properties, according to Aramco. It cured much faster, was more durable than conventional concrete, showed increased chlorine and sulphate resistance and lower water permeability.[483]

[481] Cf. (Ostovari, 2020)
[482] Cf. (Strunge, Renforth, & Spek, 2022)
[483] Cf. (Aramco, 2023)

2.9.6.3 Examples of applications of CO_2 in the building materials industry

CarbonCure

Canadian company CarbonCure develops CO_2 removal technologies for concrete producers of all sizes. The technology injects a precise amount of recycled CO_2 (previously captured CO_2) into fresh concrete during mixing to reduce its CO_2 footprint without affecting the product's performance. After injection, the CO_2 undergoes a mineralisation process and becomes permanently embedded (as $CaCO_3$) in the concrete. This improves the compressive strength of the concrete, allowing mix optimisation and a significant reduction of the CO_2 footprint as well as cost savings. [484]

Solidia Technologies inc.

Solidia Technologies was founded in the USA in 2008 and is now a BASF Venture Capital GmbH company. Solidia Technologies has developed a technology platform that enables the production of next generation building and construction materials with superior physical properties, lower life cycle costs and a low environmental footprint. Solidia's 'Low Temperature Solidification (LTS)' technology accelerates the natural bonding process of CO_2 with minerals to form solids, ensuring this happens in hours rather than years. In the building materials industry, this enables the production of stronger and more durable products. Solidia Technologies is also working on developing materials that can replace concrete. Preliminary results show that the strength and properties of these materials far exceed those of conventional concrete. Binding CO_2 in the production process offers the added advantage of creating a climate-neutral concrete substitute.[485]

2.9.7 Enhanced Fuel Recovery

Enhanced Fuel Recovery (EFR) aims to increase the yield of hydrocarbons in oil and gas reservoirs. There are various methods here. The use of CO_2 as a so-called "injection gas" is one of the most frequently used methods to improve the yield of oil and gas. This method is used intensively, especially in the USA. A CO_2 pipeline network of more than 5,500 km has even been installed there for this purpose. This method is also called Carbon Capture and Storage Enhanced Oil Recovery (CCS-EOR). In CCS-EOR, CO_2 is injected into the reservoir, increasing the pressure in the reservoir and mobilising the oil and gas trapped in the reservoir. In addition, CO_2 can reduce the viscosity of heavy oils and bitumen, facilitating the flow of oil

[484] Cf. (Carbon Cure, 2023)
[485] Cf. (BASF Venture Capital GmbH, 2023).

and gas. Using CO_2 for EFR has the added benefit of removing the greenhouse gas CO_2 from the atmosphere and storing it permanently in underground reservoirs.

Besides CCS-EOR, there are other methods used in EFR, such as the use of water or chemicals to increase the yield of oil and gas. These methods are not discussed here.

2.9.7.1 Enhanced Oil Recovery

Enhanced Oil Recovery (EOR), also known as tertiary oil recovery, refers to various technologies applied to recover oil from oil fields that have already been developed primarily (by natural pressure) and secondarily (by water flooding). EOR technologies are used to develop remaining oil deposits that can no longer be produced economically by primary and secondary methods. EOR can be carried out using various methods, including thermal methods, chemical methods and gas injection of CO_2. Gas injection with CO_2 has gained importance in recent years due to the increase in CO_2 capture technologies. Especially in the USA, but also in other regions, this method is used intensively.

The process of EOR with CO_2 involves injecting CO_2 into the oil reservoir to release the oil trapped inside. This is achieved by the injected CO_2 diluting the oil and increasing the pressure, which in turn causes the oil to expand and flow through the pores of the rock in which it is trapped.

There are several CO_2-EOR methods, including:

- Gaseous CO_2 injection: With this method, compressed CO_2 is injected into the oil reservoir.
- Liquid CO_2 injection: Liquid CO_2 is injected into the oil reservoir and then dissolves in the oil phase.
- Supercritical CO_2 injection: With this method, CO_2 is injected into the oil reservoir in a supercritical state (higher pressure and higher temperature).

Benefits of CO_2-EOR technology include increased oil production and reduced carbon emissions as CO_2 is removed from the atmosphere as a greenhouse gas and reused to produce oil.

However, the bottom line is that the method is not climate neutral, because although most of the previously captured CO_2 remains permanently in the oil reservoirs, it is used to extract new hydrocarbons from the ground, which usually result in CO_2 emissions when they are used. Other challenges include the increased costs of CO_2 capture and injection as well as the limited availability of suitable CO_2 sources or the non-existence of CO_2 networks (pipelines).

2.9.7.2 Enhanced Gas Recovery

Analogous to EOR, enhanced gas recovery (EGR) is a process for increasing natural gas production from underground deposits. In this process, CO_2 is used as a propellant to release and extract the gas from the pores of the rock. EGR is an important component of CO_2 utilisation technology and can help reduce greenhouse gas emissions.

EGR processes are used when conventional extraction methods are no longer sufficient to maintain the natural pressure in the reservoir and enable extraction. The injection of CO_2 increases the pressure in the reservoir and releases the gas from the pores of the rock.

EGR can help to increase the production of natural gas and reduce the need for new wells and reservoirs. Since most of the compressed CO_2 remains permanently in the ground and is thus removed from the atmosphere, EGR helps to build a CCS infrastructure. Compared to other CCS processes, which only involve the disposal of previously captured CO_2, CCS-EGR can generate an economic advantage. This makes it comparatively easier to establish the necessary infrastructure. For this purpose, a CO_2 pipeline network of over 5,500 km has been built in the USA.

2.9.8 Biological conversion of CO_2 in algae

The production of biomass is an important component in the energy transition, as it can contribute to the reduction of greenhouse gas emissions as a renewable energy source. For example, when biomass is used for energy, only the CO_2 quantities that have previously been bound by the plants through photosynthesis are released into the atmosphere. Biofuels are thus considered an alternative to petroleum, for example. For fuels from grain, sugar beet or rapeseed, however, huge areas of arable land would be needed, which would then be lacking for food cultivation, unless we switch to second generation processes that use cellulose-like residues. Another solution could be microalgae, which can be grown quickly and without problems.[486] Using previously captured CO_2 in the production of biomass from algae is a promising approach to make this process even more environmentally friendly and sustainable. "Algae store the energy of sunlight captured through photosynthesis in the form of sugars and fats. The fats are the really interesting thing in the search for new fuel sources, because you can get fuel from them through a chemical process whose properties are comparable to diesel fuel."[487] Compared to conventional biofuels, those from algae have the advantage that they

[486] Cf. (Decker, 2018)
[487] Cf. ibid.

grow not only in fresh water but also in salt water. They do not take up large areas of land necessary for food production, nor do they consume large amounts of fresh water. Oil extracted from algae can possibly also be processed in normal refineries into fuels that are no different from conventional diesel fuel with a high energy density.[5353] The oil can also possibly be used as a feedstock for the production of chemicals.[488]

Furthermore, the cultivation of algae can also be beneficial for climate protection reasons. Algae can convert large amounts of CO_2 and thrive even under difficult environmental conditions. They can take the carbon dioxide they need to grow and produce vegetable oil directly from the air. However, if the organisms are supplied with enriched, previously captured CO_2, not only can the growth conditions be improved. The process also offers the opportunity to provide an economically viable source of captured CO_2. Biofuels from algae thus have the potential to reduce greenhouse gases, unlike conventional fuels. In addition, there is another advantage: microalgae grow quickly and can be cultivated relatively unproblematically. Compared to land plants, the biomass yield per area and year is much higher. And compared to rapeseed, high-yielding algae cultures could produce more than ten times the amount of oil. Most importantly, microalgae cultures can be operated independently of valuable arable land.[489] Exxon Mobil, which has been researching the use of algae as a biofuel since 2009, cites further advantages of biomass from algae over the use of conventional land plants:

- **High yields:** Each hectare of algae yields more than 2,000 gallons of fuel. By comparison, palm oil yields 650 gallons (2,460 litres) per hectare, while soybean oil yields 50 gallons (190 litres) per hectare.
- **Year-round harvesting**: While other raw materials, such as maize, are only harvested once a year, this is different with algae: here, year-round and multiple harvesting is possible.
- **Water purifiers:** Algae can be grown in industrial wastewater, for example. Even more: they can clean polluted water and produce energy-rich biofuels at the same time.
- **Immediately usable:** Algae-based biofuels can be used for existing cars without the need for major adjustments to **the** engine or infrastructure requirements".

However, it is still necessary to find both the best possible algae species and the optimal cultivation conditions. In the case of algae, the focus is on the highest possible fat production and a high conversion rate from CO_2 to oil. "The microalga Botryococcus braunii, for example, is a

[488] Cf. (Exxon Mobil, no time stated).
[489] Cf. (Decker, 2018)

promising candidate. It produces large amounts of algal fat, which it then releases directly to the outside into the surrounding medium."[490]

There are both closed and open systems for cultivating microalgae. In closed systems, so-called bioreactors, the algae are cultivated in tube-shaped plastic bags, kilometre-long tube systems or plate-shaped reactors that are aligned according to the position of the sun.[537] CO_2, which was previously captured, for example, is then added here in high concentrations. "In 2012, researchers from MIT, ExxonMobil and SGI published a report in the journal Environmental Science and Technology that concluded that algae-derived biofuels, if critical research obstacles are overcome, emit about 50% fewer greenhouse gases over their entire life cycle than petroleum-based fuels."[491] However, the operation of these bioreactors is still very costly.

Experimental series are also carried out in open systems, such as shallow water basins. These are confronted with other challenges. Above all, the immigration of foreign organisms is problematic.[537]

Besides microalgae, cyanobacteria are also examples of microorganisms that can use CO_2 as a carbon source. These organisms are also able to absorb CO_2 directly from the air and use it to produce biomass. Another approach to using CO_2 in biomass production is to use methanogenic bacteria. These bacteria are able to convert CO_2 and hydrogen into methane, which can then be used as a renewable fuel. Using methanogenic bacteria to produce methane from CO_2 has the advantage that the process is very efficient and produces only small amounts of by-products. However, a source of hydrogen is needed, preferably from the electrolysis of water and renewable electricity.

The production of biofuels from microorganisms such as algae has great potential to produce substitutes for e.g. diesel with the help of previously captured CO_2. This could then be used to run the existing fleet of combustion vehicles in a more climate-neutral way than with fuels based on e.g. petroleum. However, supplying all these vehicles with algae diesel would require huge areas of bioreactors, all of which would have to be maintained and operated. This is still very expensive today. In this respect, it is of great importance that the entire production process of algae biofuel is further improved, especially from a cost perspective.

[490] Cf. (Decker, 2018)
[491] Cf. (Exxon Mobil, no time stated)

2.9.8.1 Examples of applications of microorganisms that convert CO_2

LanzaTech

The US company LanzaTech has developed a technology that uses CO_2 from industrial processes, hydrogen from water electrolysis and agricultural and municipal waste to produce biofuels. In the process, the CO_2 is ultimately converted by microorganisms, which serve as the starting material for the production of bio-ethanol. The main process steps here are gasification, compression, purification and fermentation of the feedstock. The end product bio-ethanol can be used, for example, to power the existing fleet of combustion cars in a more climate-neutral way. Or it can be used as a feedstock for the chemical industry. Ultimately, the CO_2 ends up back in the atmosphere or as agricultural or municipal waste and the process starts all over again – an example of entry into a CO_2 circular economy.[492]

2.9.9 Outlook and conclusions

2.9.9.1 Assessment of the potential of CO_2 as a raw material

The use of CO_2 as a raw material, e.g. in the chemical industry, may have the potential to reduce CO_2 emissions and at the same time produce valuable products, thus making the industries less dependent on fossil raw materials and their fluctuating prices. However, the potential of this use needs to be carefully assessed to ensure that it is indeed a sustainable alternative to conventional methods.

Factors to consider when assessing the potential of using CO_2 as a raw material in industry include:

- **Availability of CO_2** : The availability of CO_2 is an important factor in assessing the potential of its use as a raw material in industry. CO_2 is a by-product of many industrial processes. In principle, it is therefore sufficiently available. The challenge is to capture it in sufficient volume and quality and transport it to the place of its possible further use.
- **Technology development:** The technology for capturing and using CO_2 as a feedstock is developing rapidly. However, it is important to ensure that technologies are effective and sustainable, both in terms of emissions and costs.
- **Economic feasibility:** The economic feasibility of using CO_2 as a raw material depends on various factors, such as the availability of CO_2, the type of chemicals to be produced and the cost of CO_2 processing.

[492]Cf. (LanzaTech, 2023)

- **Environmental compatibility:** The use of CO_2 as a raw material can help to reduce CO_2 emissions. However, it is important to ensure that the use of CO_2 is indeed environmentally sound and that the environmental impacts of CO_2 capture and processing and the necessary accompanying processes are taken into account. An example is the mining of calcium silicate minerals as a starting point for CO_2 mineralisation. Here, care must be taken to ensure that the environment is affected as little as possible by the mining process.
- **Market potential:** The potential for using CO_2 as a feedstock also depends on market demand. It is important to assess the market potential to ensure that the use of CO_2 as a feedstock is economically viable. Nova sees in a press release that more and more companies are interested in CCU technologies.[493]

2.9.9.2 Outlook for future developments and trends in this area

In the future, the use of CO_2 as a raw material in industry is likely to increase. There are several developments and trends that point to this:

- **Advances in CO_2 capture technology:** New CO_2 capture technologies are being developed and old ones are being improved to increase the quantity and quality of CO_2 collected and reduce costs (see also chapter 2.8).
- **Increase in government incentives and regulations**: Governments around the world are implementing incentives and regulations to encourage the reduction of CO_2 emissions. These policies could further drive the use of CO_2 as a feedstock in industry. A global cap-and-trade system for pricing and trading CO_2 allowances (analogous to the EU ETS) would further increase (economic) incentives.
- **Growing awareness of sustainability**: Consumers and businesses are becoming more environmentally conscious and are looking for products and manufacturers that are environmentally friendly. The use of CO_2 as a raw material in industry can be an important step towards sustainability, which could further increase the interest of companies and consumers in these products.

New products and applications: The use of CO_2 as a raw material enables the production of new products and applications that were not possible before. Examples include synthetic fuels, polymer materials and building materials. It is expected that these products and applications will develop further and lead to a wider use of CO_2 as a raw material.

[493] Cf. (Nova Institute , 2023).