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Contribution to the discussion on the evaluation of Carbon Capture and Utilisation

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CO2
CCU

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Summary

In the discussions on how to achieve greenhouse gas neutrality, CCU measures (Carbon Capture and Utilization) are repeatedly cited as a quick solution for achieving greenhouse gas neutrality in industry. CCU measures seem to be favourable, since the substitution of fossil based products may reduce the fossil emissions from the substituted products. However, a holistic view on all emissions in the CCU process chain is necessary. From the high energy demand fossil emissions will stem as long as the energy system is not converted to full renewability.

CCU means using emitted carbon, especially carbon dioxide for example from industrial applications instead of just releasing it into the atmosphere. One possibility is using it in combination with power to gas/liquid plants to produce fuel, another to produce feedstock for the chemical industry.

Where carbon is used several times, emission is shifted all the way downstream of the last use. This recirculation only leads to a temporal and local shift, but not to a reduction of the original emissions. Thus, a CCU action is not a climate protection action that can mitigate fossil fuel emissions relevant to greenhouse gas emissions. So, it is always the carbon source that determines how and if CCU affects our climate.

Additionally the emissions from the energy conversion for the CCU process chain has to be regarded. Because of the limited energy efficiency of the CCU process today about double the amount of energy is needed to exchange a fossil reference product by a CCU product. As long as electrical energy in Germany is not used exclusively from renewable power, energy expenditures for CCUs will therefore generate additional greenhouse gas emissions. As a result, it only makes sense at this time to move forward with technology development and only integrate CCU measures, when sufficient renewable energy is available.

This paper is intended to contribute to the scientific and political debate on carbon capture and utilization and gives an overview of the effect from different perspectives. Key priorities in this context are rapid greenhouse gas reduction and sustainable greenhouse gas neutrality. The result is an evaluation according to aspects of climate protection as well as the future supply of raw materials.

1. CORE MESSAGE

For effective climate protection fossil greenhouse gas emissions must be reduced first and foremost.

Germany is aiming for greenhouse gas neutrality by 2045 and Europe by 2050 at the latest. The highest priority in terms of the precautionary principle is to avoid the generation of carbon dioxide and other greenhouse gas emissions. This requires many changes in economy and society both on the demand side and in production. Especially in the field of energy supply but also in industrial production technological innovations are needed both for further development of many known technologies and for new ones to be developed.

By switching to renewable energies, it is possible to completely avoid energy-related greenhouse gas emissions. In order to use energy and natural resources efficiently, renewable electricity must be used directly wherever it is technically possible.

Industrial processes must be converted and further developed both to fully renewable energy sources and to low-GHG raw materials. The top priority everywhere is to avoid the generation of carbon dioxide entirely.

2. CORE MESSAGE

CCU based on fossil carbon is not a substitute for mitigating fossil greenhouse gas emissions.

If fossil carbon dioxide is captured by means of CCU and used elsewhere, this CO_2 always enters the atmosphere at the end of the use chain, regardless of the number of subsequent uses. This example applies to carbon emissions from industrial production processes such as cement, lime and glass production, which, according to current knowledge, are technically unavoidable. In this context as well, it is important to continuously promote innovations with the aim of avoiding or at least reducing greenhouse gas emissions, which are unavoidable from today's perspective, through ongoing developments and advances in knowledge.

If such carbon is used with CCU actions to produce synthetic fuels, emissions to the atmosphere are only shifted in time and place. Fossil carbon dioxide is no longer emitted by industry but elsewhere. However, this makes no difference to the resulting climate effect. This is illustrated in Figure 5. For effective climate protection, the avoidance of fossil greenhouse gas emissions and the substitution of fossil energy sources and products shall be pursued primarily.

3. CORE MESSAGE

Unavoidable greenhouse gas emissions shall be compensated to achieve greenhouse gas neutrality. CCU measures cannot contribute to compensation.

Beside the above-mentioned process emissions from industry unavoidable from today's perspective, it must be assumed that greenhouse gas emissions from agriculture in particular will not be completely avoidable in the long term, despite the potential for technological development. Unavoidable greenhouse gas emissions can only be compensated by removing carbon from the atmosphere and by long-lasting and safe sequestration of this carbon.

CCU actions are not a substitute for this required compensation because carbon is only used several times and not permanently sequestered. Additional, permanent carbon removal from the atmosphere (CDR – Carbon Dioxide Removal) is required. As an example, this can be done by preserving and developing natural carbon sinks such as forests and peatlands. This means that full compensation of unavoidable greenhouse gas emissions from industry, agriculture and the waste/wastewater sector is possible on a sustainable basis in Germany. This is shown by the UBA in its RESCUE study (2019).

4. CORE MESSAGE

CCU with atmospheric carbon has the potential to permanently omit further anthropogenic greenhouse gas emissions.

If carbon is removed from the atmosphere and then re-emitted this leads to a closed cycle regardless of amount of uses, with no additional emissions caused by humans. This requires, however, that no further greenhouse gas emissions are generated along the entire process chain of CCU measures and that only renewable energies are used for energy-related expenditures. Synthetic fuel, power, and chemical feedstocks with CCU from atmospheric carbon in contrast to CCU with fossil carbon will then not result in any greenhouse gas-relevant emissions within the application areas of transport, heat, and industry. This is illustrated in Figure 4.

5. CORE MESSAGE

Carbon dioxide is permanently needed as a raw material source for carbon compounds. CCU, including atmospheric carbon, will therefore be an indispensable component for future economic activity in the long term.

On a long-term basis, hydrocarbons will also be needed in an efficient and greenhouse gas-neutral economic system such as for air and sea transport and for the chemical industry. One possible highly efficient source of raw materials is the mechanical or chemical recycling of carbon-containing products. However, this is expected to meet only a portion of the demand, requiring long-term and permanent CCU actions to extract carbon as a feedstock source. Therefore, CCU must be used to meet further demand – from the atmosphere or from sources that are currently seen as unavoidable in the long term. All technology development for the effective sequestration of carbon from atmosphere has to be supported in order to have them handy for large scale application in future.

6. CORE MESSAGE

CCU leads to additional emissions in today’s power system due to remaining large shares of fossil power plants. Nevertheless the availability of the technology for a future defossilised economic system should be safeguarded.

CCU requires a lot of energy. If a larger portion of this energy itself is still derived from fossil fuels such as coal or gas, the continued use of emissions by means of CCU becomes highly inefficient and even harmful to the climate. Fossil fuels would then become fuels again through a significant detour. This has no energy benefits and inevitably leads to significant additional emissions of greenhouse gases. Therefore, CCU measures should only be applied from a very high share of renewable energies in the power system (order of magnitude above 80%). Anything else would jeopardize short- and medium-term climate protection targets. A fast build-up of resources of renewable electrical energy is prerequisite for the integration of CCU measures in the industrial system. In order to have the CCU technologies ready-for-use research and development and technology transfer should be safeguarded and supported already today. The early development support is required for a circular carbon economy within a defossilised economic system.

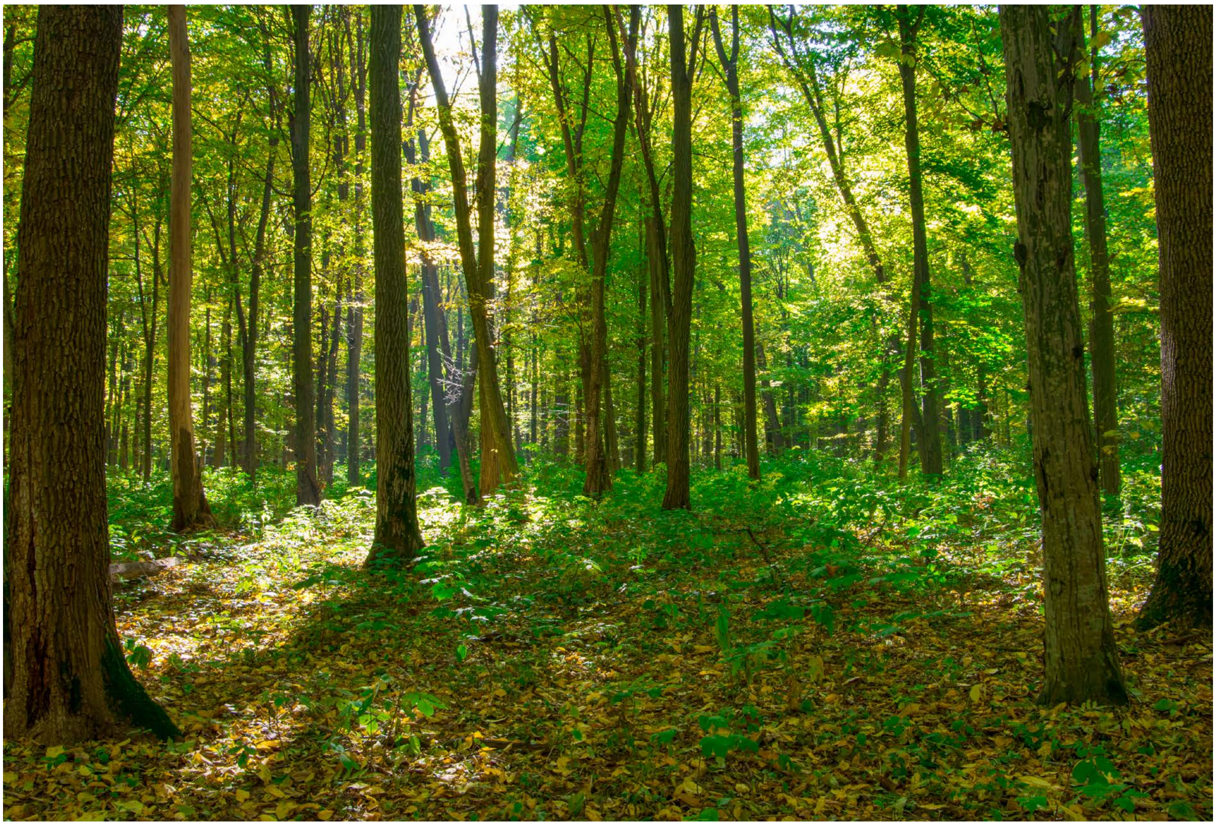
CONCLUSION:

CCU in combination with fossil greenhouse gas emissions cannot make a sustainable contribution to climate protection. This also applies to unavoidable greenhouse gas emissions from industry. Regardless of how often fossil carbon is reused, this always leads – at the end of multiple uses – to additional greenhouse gas emissions into the atmosphere and thus contributes to climate change.

A complete decarbonization of the economic system is not possible according to current knowledge. Carbon is needed for selected fuels and raw materials in the chemical industry. This makes CCU measures an indispensable component of a future economic system in the long term. For this purpose, only CCU actions where the energy demand is met exclusively with renewable energy and which use only atmospheric carbon are to be assessed as greenhouse gas neutral.

The availability and further technical development of CCU technologies and the renewable energy volumes required for a circular carbon economy within a defossilised economic system shall be ensured against this background. At the same time, it must be guaranteed that this does not create any dependencies hindering greenhouse gas-neutral economic activity. In the short and medium term, only research and demonstration projects in selected industrial sectors and CCU technologies using atmospheric carbon dioxide should be supported and promoted to a limited extent. Otherwise, under the current parameters, there would be additional emissions by the energy industry, especially in the next decade.

Irrespective of the permanent carbon requirement, it is important to promote innovations and developments with the aim of further reducing greenhouse gas emissions that cannot be avoided according to current knowledge.



2. Introduction

In 2015 the parties to the Framework Convention on Climate Change agreed in the Paris Agreement (PA) on a joint action for fighting against climate change. The goal is to keep global warming significantly below 2 °C compared to pre-industrial levels, as well as to make efforts to limit temperature increases to 1.5 °C. With the ratification of the PA and the commitment at the United Nations Climate Summit in 2019 to pursue greenhouse gas neutrality by 2050 as a long-term goal, Germany has entered into these stricter international obligations. The Climate Action Plan 2050 from 2016 [BMU 2016] defined sectoral contributions to greenhouse gas mitigation by 2030, which were legally anchored with annual and sector-specific greenhouse gas mitigation targets in the Federal Climate Change Act in 2019 [BMU 2019a]. Apart from the target of mitigating greenhouse gases by 55% by 2030 compared to 1990, the overarching environmental action goal of "greenhouse gas neutrality" for Germany by 2050 was also anchored in that respect. However, an increase in ambition, which would also be urgently required against the background of the PA, was not undertaken for the time horizon by 2030 [see UBA 2019b]. However, this was not achieved until the amendment of the Federal Climate Protection Act in the summer of 2021. Greenhouse gas neutrality was targeted for the year 2045 and a reduction of 65% by 2030 and 88% by 2040 compared to 1990. In order to realise the long-term transformation towards a greenhouse gas-neutral Germany, major changes are required in all areas of our everyday lives and in the economy. The premises for making this successful are the avoidance and substitution of greenhouse gas-intensive processes and products and an energy supply based entirely on renewable energies [UBA 2019c]. Thus, both mitigating process and energy-related greenhouse gas emissions and mitigating the demand for fuel, power and raw materials can be achieved in the long term.

In the course of political and scientific discussion on the design of greenhouse gas neutrality, the contribution of CCU (Carbon Capture and Utilisation) measures is repeatedly debated at national and European level. CCU refers to the use of captured carbon (mostly in the form of carbon dioxide, CO_2) as a raw material to provide products and energy sources. The German government's Climate Action Programme 2030 for the implementation of the Climate Action Plan 2050 already specifically addresses CCU measures in the industry sector [BMU 2019b]. In this context, even fundamental questions as to whether and how CCU measures can make a contribution in a greenhouse gas-neutral economic system and along the way as well as how this can be designed in a way that serves the system have not yet been sufficiently illuminated and are presented differently by the various stakeholders depending on their interests.

The aim of this paper is to systematise the debate on the assessment of CCU measures from the perspective of the German Environment Agency in order to fundamentally assess the impact of CCU in a greenhouse gas neutral[1] Germany and along the way. For this purpose, guidelines and criteria for the evaluation of CCU measures are presented. These allow a conceptual classification of whether or not CCU measures should be pursued for climate policy or other reasons. However, they do not allow for an assessment of specific implementation examples, financial support decisions of research and demonstration projects, and evaluations against the background of monitoring and reporting rules in EU emissions trading.

1 The term "greenhouse gas neutral" is also used here synonymously for "largely greenhouse gas neutral", i. e. a planned reduction of 95 percent. This distinction is not relevant for the assessment of CCUs in this paper.

3. What does CCU mean?

„Carbon capture and utilisation“ refers to the capture, transport and subsequent use of carbon, usually in the form of CO_2 or CO, in which carbon is fed into at least one further utilisation cycle. Depending on the origin and use of carbon, this requires the combination of different processes and process steps, each of which is associated with energy or resource consumption as well as environmental impacts.

Carbon: Carbon can exist in different forms and result from different origins, the latter is summarised in a simplified way in Figure 1. Often, CCU is understood as the use of gaseous carbon dioxide[2]. This can be of fossil origin (from fossil energy sources or fossil raw materials, e.g. limestone) or origin from the atmosphere (from biomass or air).

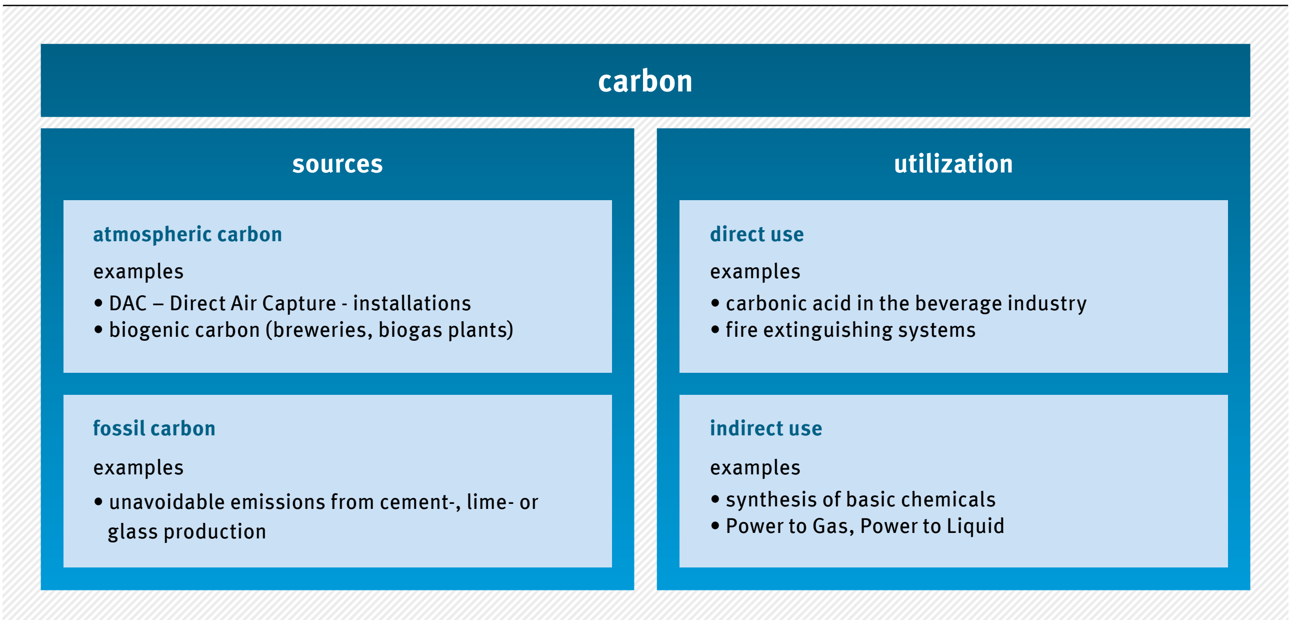
Capture: Capture describes the entire process chain of collecting, transporting and preparing carbon for subsequent use. This includes, for example, capture, separation and transport of carbon dioxide from a gas mixture or the atmosphere, as well as the incorporation of atmospheric carbon dioxide into biomass.

Utilisation: Carbon can be used directly or indirectly to provide carbon-containing products. Direct use of carbon dioxide is, for example, the use of carbon dioxide in fire extinguishing systems. Indirect feedstock use includes the synthesis of basic chemicals or (intermediate) products of the chemical industry and final energy carriers that can be used in transport, industry and heat supply. This is called power to gas/liquid/solid – see Figure 1 and excursus 1.

2 In the following, “carbon” or “carbon dioxide” will be referred to as “carbon source” for linguistic simplification – other carbon compounds, e.g. carbon monoxide, are then implicitly covered.

Figure 1

Schematic overview



Source: German Environment Agency

Excursus 1: Power to Gas/Liquid/Solid

Power to Gas (PtG) in combination with CCU is understood to mean the production of methane, Power to Liquid (PtL) the production of liquid hydrocarbons and Power to Solid (PtS) the production of solid hydrocarbons, for example plastics of any kind, using electrical energy. Power to chemicals is often used as a generalisation when organic chemical compounds – regardless of their physical state - are made available.

What they all have in common is water electrolysis as the first necessary step. In this process, water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) using electrical energy. Hydrogen can then react with carbon dioxide in a catalytic chemical or biological synthesis, with further energy input, to form methane or other substances. In PtL, a hydrogen/carbon monoxide or hydrogen/carbon dioxide mixture is first generated and converted to hydrocarbons in a synthesis. Energy requirements for this tend to increase as the number of processes in the process chain from hydrogen to liquid or solid hydrocarbons increases.

Carbon from waste and residual biomass in, for example, combustion, gasification, pyrolysis or fermentation plants can also be used in combination with PtG/PtL/PtS plants and further energy input.

Hence synthetic energy carriers or raw materials can be made available, which can substitute fossil energy carriers and raw materials in all areas of application (transport, heat, electricity, chemical industry) (cf. chapter 5.2).

Within this paper CCU is not understood to mean the direct storage of CO_2 as “Carbon Capture and Storage” (CCS)[3] or the use of carbon dioxide in the extraction of crude oil (“Enhanced Oil Recovery” – EOR). Nor does this paper address the alteration of natural carbon sinks such as land use, land use change or afforestation, or the production and use of wood-based products, which equally sequester and store carbon from the atmosphere. Chemical recycling[4] is also not referred to as CCU here.

3 Or combinations of techniques with subsequent storage (CCUS).

4 Chemical recycling or feedstock recycling is the conversion of plastic polymers into their monomers or chemical building blocks by means of thermochemical or chemical processes. Gasification, pyrolysis, oiling or solvolysis are the main technical processes that can be considered for this purpose. At present, however, this is not the state of the art in plastics recycling [UBA 2020c].

4. Elements of CCU – Evaluation

For an initial overview, the aspects to be considered in the evaluation of a CCU measure are named below, initially in simplified form, and then discussed in more detail in chapter 5 and chapter 6.

Evaluation of avoidability: The individual process stages of a CCU measure involve a high input of energy. This starts with provision, for example to extract carbon dioxide from a gas mixture (e.g. flue gas or the atmosphere), and also applies to the production of so-called PtG/PtL/PtS products. With the goal of sustainable development and the challenges of designing a greenhouse gas-neutral energy system, energy should be used as efficiently as possible in technical applications. Accordingly, top priority is to avoid the generation of CO_2. Evaluation of a possible CCU measure shall therefore always be started by considering whether CO_2 needs to be generated at all. Only if CO_2 generation associated with a production process is considered unavoidable or CO_2 is taken from the atmosphere a CCU measure should be considered at all and evaluated against the following criteria.

Evaluation of the climate protection impact: In this context it is considered whether and to what extent greenhouse gas emissions can be saved through the CCU measure compared to the respective current status. The evaluation of the climate protection impact includes all greenhouse gas emissions that are directly and indirectly associated with all sub-steps of the CCU measure, as presented in chapter 5. When evaluating the climate protection effect, it is also important to estimate the time span in which greenhouse gas emissions can be saved through a CCU measure.

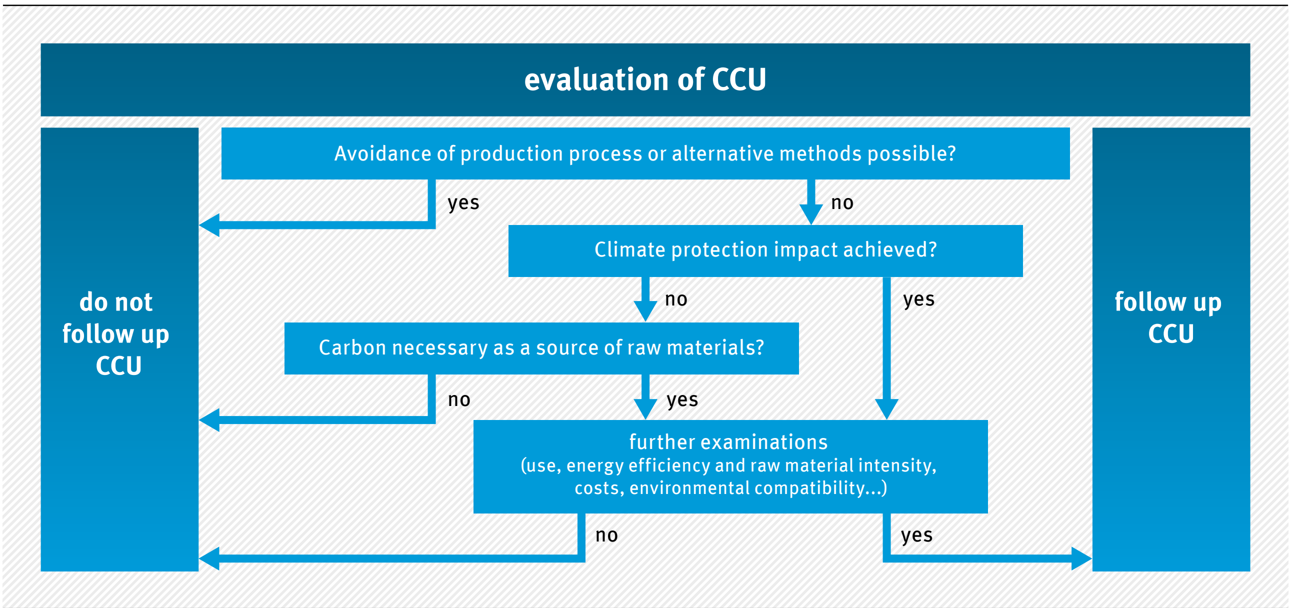
Evaluation as a source of raw materials: Even in a future greenhouse gas-neutral society, carbon will be needed to provide energy sources and a variety of products. Again, the question of avoidability shall be asked first and it shall be verified whether a carbon-containing product shall be manufactured at all or whether carbon-free alternatives might be used. If the demand for carbon cannot be met through direct, energy-efficient mechanical recycling measures or from sustainable biogenic residues, other circular carbon sources need to be used in a greenhouse gas-neutral society.

Further examinations: In addition to the aforementioned three essential criteria, other environmental impacts of the respective CCU measures shall be considered to ensure that no other serious adverse environmental impacts occur. Furthermore, questions such as the economic operation of a plant shall also be addressed.

In summary Figure 2 shows the possible process of evaluating CCU measures.

Figure 2

Schematic representation of the procedure for the evaluation of CCUs



Source: German Environment Agency

5. Climate protection effect of CCU

A climate protection measure enables mitigation of greenhouse gas emissions in order to counteract human-induced global warming and prevent or mitigate the negative impacts on ecosystems, flora and fauna and human health.

The stakeholders from the fields of science, business/industry and politics involved in the debate on the development and use of CCU technologies differ greatly in their motivation and approach. Accordingly, they currently come to different conclusions as to what benefits CCU measures may have today and in the future. Often the transparent presentation of the approaches, i. e. objectives, time horizon[5] and system boundaries[6] necessary for an evaluation are missing.

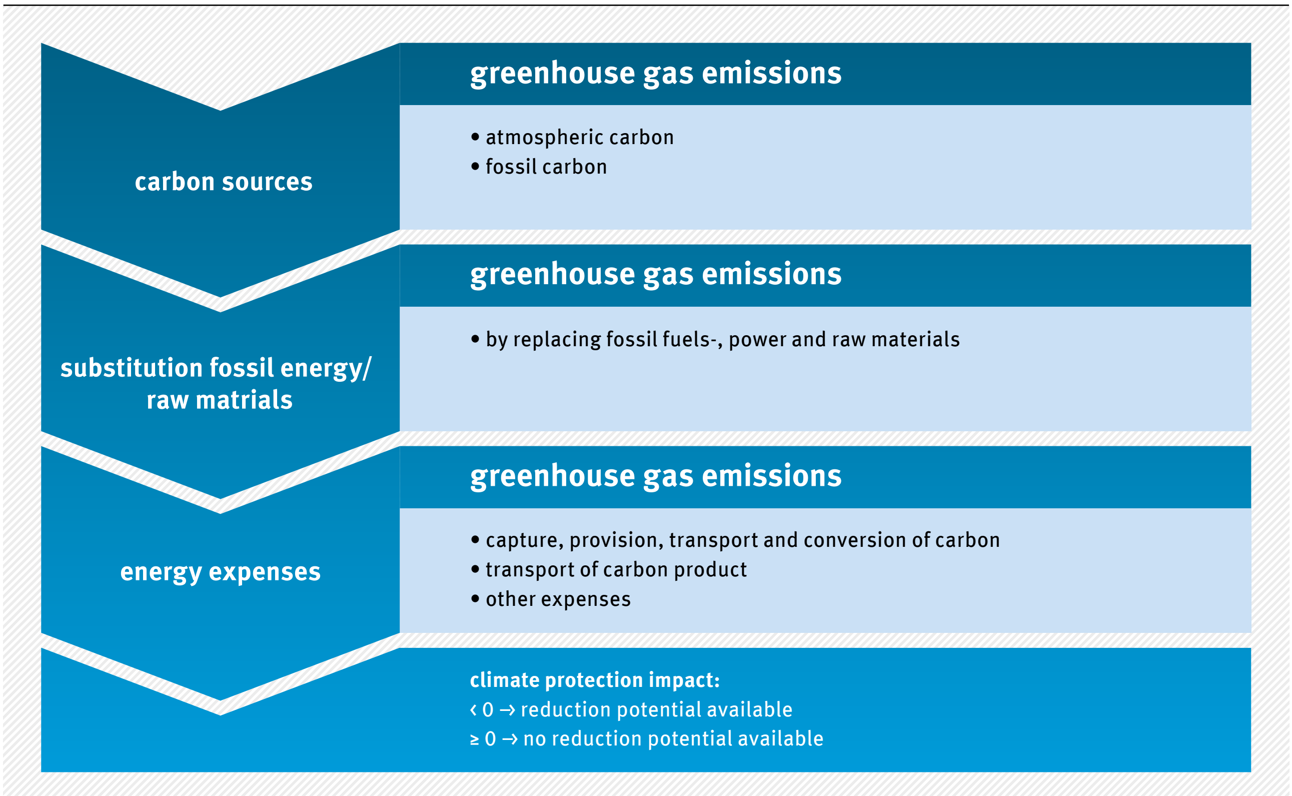
This chapter will present basic considerations on the climate protection impact of CCU actions from the viewpoint of the German Environment Agency. Basically, it is determined by three main influencing factors:

5 Depending on the respective stage of development, the intended time of application and the existing economic and technical framework conditions, there are different reference periods that are decisive for the result of the evaluation. Thus, an evaluation can be based on the current actual state or on a predicted state at a later time. The time period considered may also differ and should be explicitly presented in the evaluation.

6 Similarly, to the procedure for preparing life cycle assessments, the boundaries of the system under consideration shall be made clear. This is a necessary prerequisite to be able to understand which aspects have been considered in a qualitative and quantitative evaluation and which have not. A technology that is viewed positively within narrow limits can have a negative effect in a larger system context and vice versa.

Figure 3

Schematic representation for evaluating the climate protection impact



Note: The greenhouse gas emissions for the CCU product are considered with a positive sign and those for the conventional (to be substituted) product with a negative sign.

Source: German Environment Agency

- from the carbon source used,
- from the effect of the CCU product by substituting fossil energy sources or raw materials and
- from greenhouse gas emissions for energetic expenditures for the provision and use of carbon in the process chain.

While the first aspect can basically be considered irrespective of time horizon, the last two aspects have different effects depending on the point in time, especially in the transformation pathway towards a sustainable energy system based entirely on renewable energies. In summary Figure 3 schematically illustrates a procedure for calculating the climate protection effect.

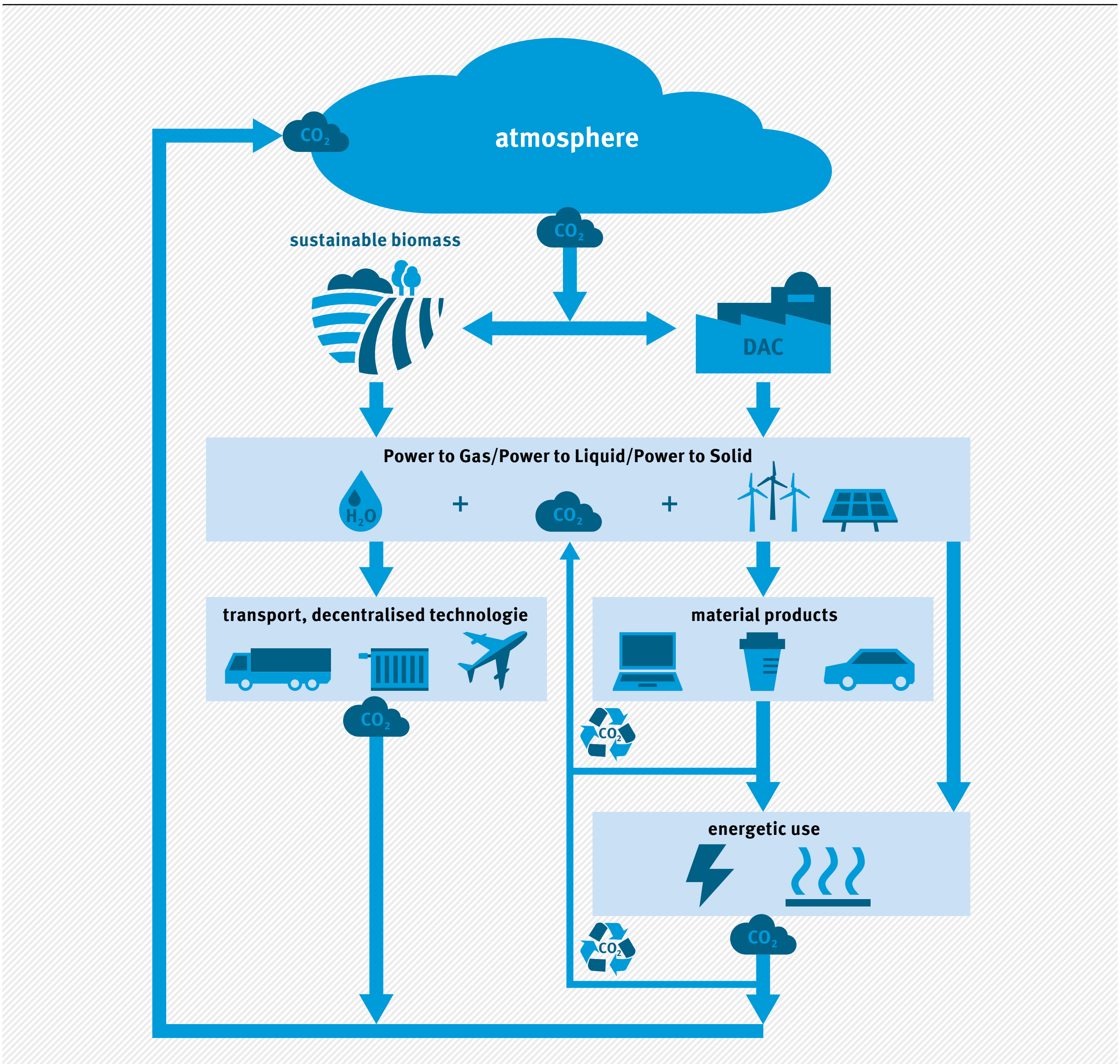
5.1 Climate protection impact of the carbon source

5.1.1 Atmospheric carbon source

As shown in Figure 1 previously, different carbon sources are available for a CCU measure. Carbon from biogenic sources is usually derived from atmospheric

Figure 4

Schematic representation for the use of atmospheric carbon sources for CCU



Source: German Environment Agency

carbon and thus in most cases[7] has the identical effect as direct air capture (DAC) of CO_2 from the atmosphere, so they are considered together below. Carbon is removed from the atmosphere through photosynthesis or technically by means of DAC. The provision of carbon for CCU measures is always accompanied by energy expenditures, for example for collection, processing and transport. The subsequent production of carbon-containing energy carriers or raw materials requires the use of further energy and substances (see also Excursus 1).

Potentially carbon can be used over and over again, see chapter 5.1.3. Regardless of how often carbon is captured and used in products or substances, carbon from atmospheric sources releases exactly the same amount of carbon back into the atmosphere at the end of its use as was originally removed from it. In the case of CCU measures in combination with atmospheric carbon, greenhouse gas emissions can thus only be reduced compared to the current situation (without CCU) through the substitution of fossil energy sources or raw materials (see chapter 5.2). **The removal of carbon from the atmosphere and its subsequent release back into the atmosphere leads to a closed cycle with no additional emissions caused by humans. The prerequisite for this is that no further greenhouse gas emissions occur during the CCU measure.** This can be achieved, for example, through the exclusive use of renewable energies (e.g. electricity, heat) as well as sustainably produced auxiliary materials, see chapter 5.3. The described pathway and its effect are summarised graphically in Figure 4.

5.1.2 Fossil carbon source

The use of fossil carbon in CCU measures and their climate protection impact is shown in Figure 5. When considering this carbon source, it is also assumed here that no further greenhouse gas emissions are generated during the entire CCU measure, for example by using only renewable energies for the respective CCU measure (for this, see chapter 5.3). However, this does not affect the climate impact of the carbon source.

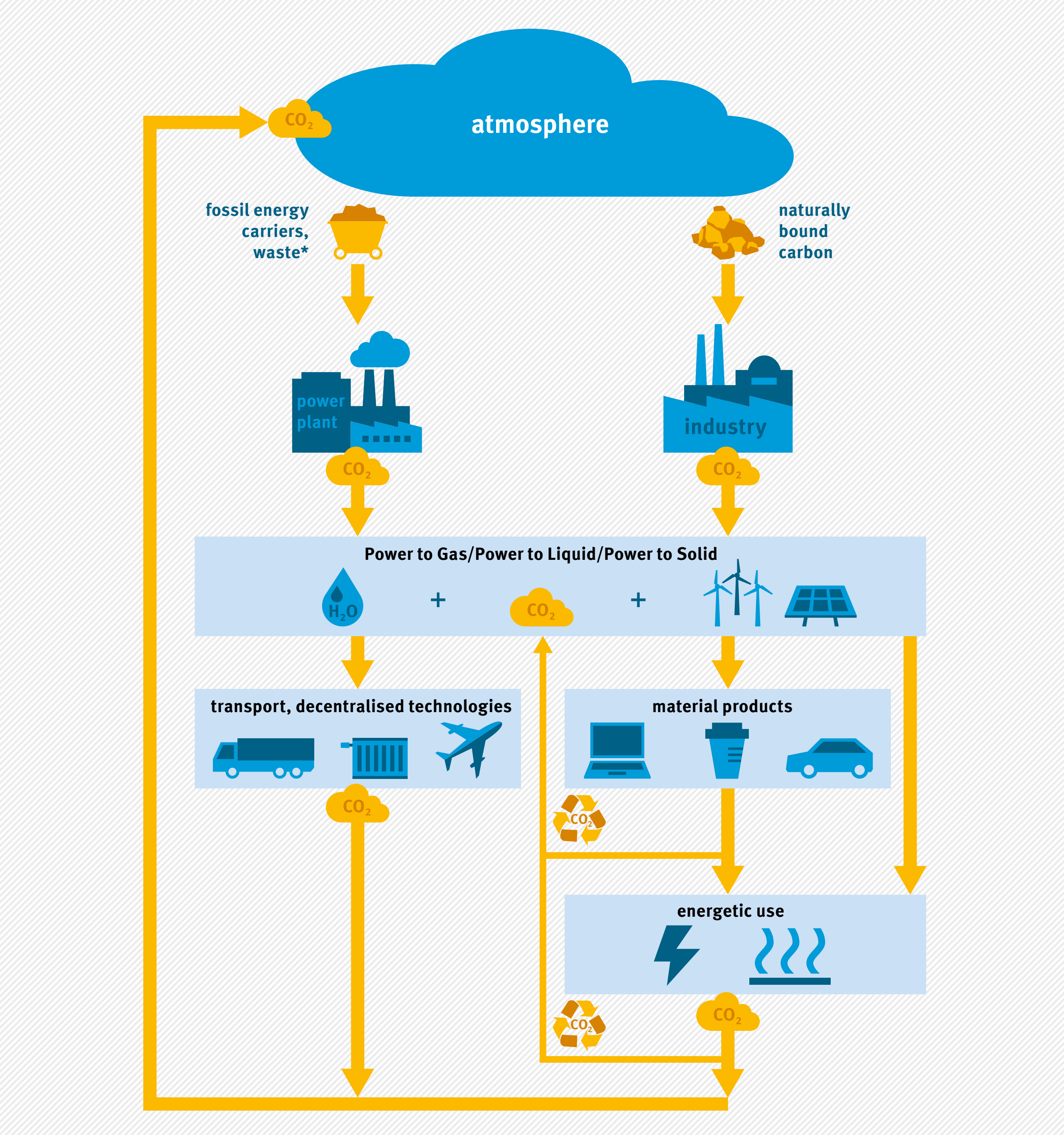
The fossil carbon could, for example, come from a previous energy use or from industrial processes (left-hand path in Figure 5). In some production processes, such as cement, lime and glass production, naturally bound carbon is also released, e.g. from carbonate rock (right-hand path in Figure 5). **Regardless of the number of times fossil carbon is reused, this always results in greenhouse gas emissions into the atmosphere, even at the end of multiple uses by means of CCU measures and thus to an increase in the human-induced climate effect.** Therefore, no positive climate protection impact can be achieved through the use of fossil carbon in CCU measures.

The aim is to avoid any human-induced carbon emissions and thus to develop and use greenhouse gas-neutral alternatives for the first process step. Alternative options based on renewable energies have already been discussed for the substitution of fossil carbon in all energy applications and largely all material uses in the chemical industry. The production of iron and steel from iron ore can be almost greenhouse gas neutral with the direct use of green hydrogen as a reducing agent (cf. chapter 5.4.1). In contrast, the substitution of many processes with raw material-related greenhouse gas emissions is only at an early stage of development or still unresolved, as in the cement, lime or glass industries. If the products from these processes are necessary for society and no greenhouse gas neutral alternatives are available for the products or the production processes, this is inevitably accompanied by the release of additional greenhouse gas emissions.

7 For the investigation of the carbon source it is sufficient to assume that CO_2 that is taken from the atmosphere is re-emitted there at the end and is thus neutral in the carbon footprint. Storage in biomass is not considered according to the definition in chapter 3.

Figure 5

Schematic representation for the use of atmospheric carbon sources for CCU



Note: *If the chemical industry increasingly produces renewable electricity-based carbon products, the waste energy source (currently with an average biogenic share of 50% for residual waste) will no longer fall into the "fossil carbon" category in the long term.

Source: German Environment Agency

5.1.3 Multiple carbon use

Basically, material cycles with multi-stage use shall be aimed for, i.e. in this case a carbon cycle. Multiple use can contribute to systemic efficiency, as the use of atmospheric carbon in particular is associated with higher energy expenditures than the capture from concentrated gases.

However, in the case of decentralised energy use or applications, e.g. in the transport sector, recovery of the emitted carbon is hardly possible. In this case multiple use can only be realised through recovery from the atmosphere and the additional effort required in this process [UBA 2014]. In fixed applications (industrial point sources and central electricity and heat supply) the capture and use of oxidised carbon is technically feasible (see Figure 4 and Figure 5). However, it is to be noted that carbon needs to be available at the site of the PtG/PtL/PtS plant or shall be transported there incurring further expenses.[8]

An utilisation cycle of hydrocarbons is always subject to the principle of thermodynamically irreversibility. When synthesising a hydrocarbon with the starting product of oxidised carbon (CO, CO_2) the binding energy released in the previous chemical reaction (e.g. combustion) first has to be applied again. Other factors are compensation of efficiency losses of the preceding combustion and additional energy required for the subsequent chemical synthesis. In technical systems additional energy is always required to compensate for efficiency losses. Accordingly, the use of synthetic hydrocarbons as fuel always leads to energy losses compared to, for example, direct, grid-connected renewable electrical energy.

Multiple carbon use does not change the climate impact of the original carbon source, as the carbon is ultimately always emitted into the atmosphere as carbon dioxide, where it exerts its greenhouse gas effect. Fossil organic carbon that is used in industrial production processes and is technically unavoidable therefore always leads to an increase in human-induced carbon dioxide concentration in the atmosphere, regardless of the number of subsequent uses with CCU.

8 In long-term scenarios energy-economic optimisations essentially outline an import of PtG/PtL/PtS products. Accordingly, a large distance would have to be covered and additional energy expenditures would have to be made for the recycling and transport of carbon to the location of the PtG/PtL/PtS plants (cf. [BDI 2018]; [DENA 2018]; [Öko-Institut 2015] or [UBA 2014]).

5.2 Climate protection impact in the substitution of fossil energy sources or raw materials

After the carbon source, the second aspect in assessing the climate protection impact of CCU measures is the substitution effect of a CCU product in replacing fossil fuels, power or raw materials. For simplification purposes, this analysis also assumes the complete use of renewable energies for all energy-related consumptions.

The various PtG/PtL/PtS technologies have different substitution potentials, as the fossil energy sources to be replaced cause different levels of greenhouse gas emissions during their use and depending on the application technology. Basically, it has always to be considered that PtG/PtL/PtS is often not the only renewable alternative for the respective application. In Figure 6 an overview of the substitution effect is given on an approximate basis and with simplifying assumptions. It becomes apparent that, for example, significantly more natural gas can be substituted for the provision of space heating via Power to Heat in combination with heat pumps than if renewable gas is provided via Power to Gas and then used in conventional technologies [UBA 2016a]. At the same time it is to be considered that also non-electricity based renewable energies can be used for heat supply. Generally speaking the integration of substitution technologies is to be designed in such a way that the most effective possible contribution to achieving the medium-term climate protection and energy efficiency targets is ensured [UBA 2016a]. **Accordingly, it makes sense to give preference to efficient technologies and to integrate technologies with high substitution potential earlier in the course of the transformation process towards a sustainable economic system than technologies with lower substitution potential** [UBA 2016a]. As shown in Figure 6 the PtG/PtL technologies that are directly connected to CCU (see the last three lines) have relatively low substitution potentials. Nevertheless, it is necessary to redesign industrial processes to reduce or neutralise greenhouse gas emissions. For example, in the case of steel industry, converting to a production with largely neutral greenhouse gas emissions is possible and development should be started immediately despite the low substitution potential of PtG hydrogen, because the investment cycles are long and a far-reaching conversion of production facilities is required.

Figure 6

substitution effect of selected PtX technologies

Use of regenerative power			Substitution of fossil supply				
regenerative supply			fossil reduction			Substitution ratio	avoided greenhouse gas emissions in CO_{2eq}
Input	Technology	Supplied end-/use energy		Technology	Input		
1 kWh regen. power	PtH Heat pump	3,3 kWh (thermal)	3,3 kWh (thermal)	Condensing boiler (105 %)	3,14 kWh natural gas	3,14	~ 640
1 kWh regen. power	e-car (80 %)	4,6 km	4,6 km	combustion engine (28 %)	2,6 kWh liquid fuel	2,6	~ 690
1 kWh regen. power	PtH Direct electric	0,95 kWh (thermal)	0,95 kWh (thermal)	Condensing boiler (105 %)	0,91 kWh natural gas	0,91	~ 185
1 kWh regen. power	PtG–H2 material	0,74 kWh (hydrogen)	0,74 kWh (hydrogen)	Steam reforming (85,2 %)	0,87 kWh natural gas	0,87	~ 180
1 kWh regen. power	PtG–CH4	0,58 kWh (methane)	0,58 kWh (methane)		0,58 kWh natural gas	0,58	~ 120
1 kWh regen. power	PtL	0,5 kWh (liquid fuel)	0,5 kWh (liquid fuel)		0,5 kWh liquid fuel	0,5	~ 135

Note: All specifications refer to the use of 1 kWh of renewable electricity.

Source: [UBA 2019b]

5.3 Climate protection impact of energy consumption of a CCU measure in the transformation pathway

For the sake of simplicity, the illustrations in chapter 5.1 and 5.2 assume the exclusive use of renewable energies in the CCU measure. In the transformation pathway towards an energy supply based entirely on renewable sources, however, this is not the case as far as grid-connected plants[9] are concerned. In the case of grid-connected CCU measures, the greenhouse gas emissions actually caused for energy consumption are highly dependent on the time of electricity use. It therefore matters whether renewable electricity is available at the time of electricity use or additional fossil energy sources have to be used to meet the additional energy demand of a CCU measure. The scientific determination of the real greenhouse gas reduction effects of additional electricity consumers is complex and can only be determined in the interaction of all electricity producers and consumers as well as their flexibilisation [UBA 2016a]. Furthermore, the climate protection effect of the CCU measure is significantly influenced by energy efficiency of each individual process stage (capture, transport, product manufacturing technology, etc.) in the pathway.

Current regional "surplus of electricity"[10] is not sufficient for the economic operation of CCU measures and will probably not be sufficient in Germany in the next decade. Indeed, **under the current framework conditions of the electricity supply system, any expansion of grid-connected CCU measures in Germany would lead to a higher utilisation of conventional, fossil-based electricity generation [UBA 2016a]. In practice this would result in a lossyenergy conversion of fossil fuels to gas (coal/gas to gas), to liquid fuels (coal/gas to liquid) or solid products (coal/gas to solid).** Under the conditions of using fossil energy sources for the production of electrical energy in PtG plants, for example, a product would thus be produced,

9 According to [UBA 2016a] and 37. BImSchV.

10 This refers to periods of high renewable electricity production that cannot be integrated into the electricity system and, above all, lead to grid-related curtailments of renewable energies.

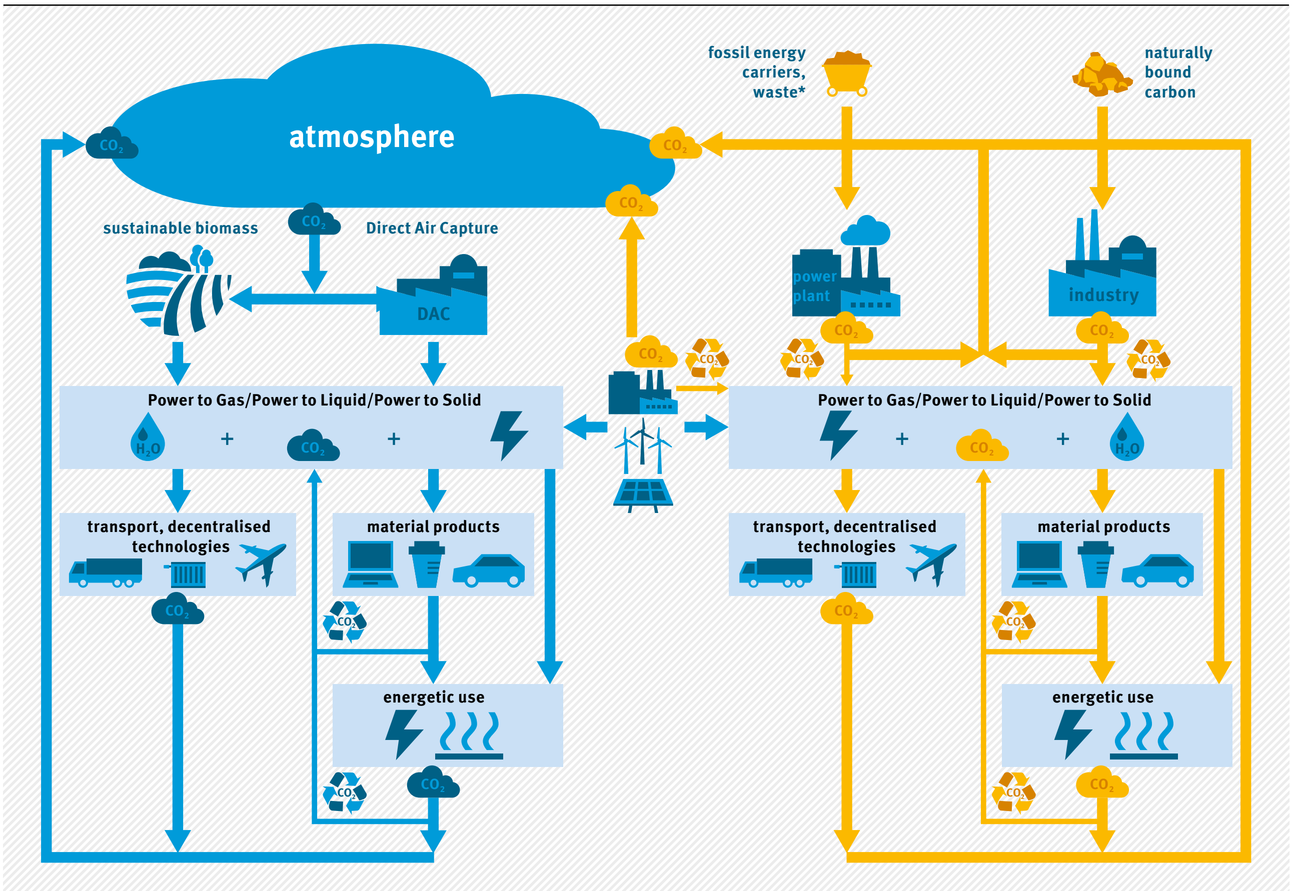
irrespective of the carbon source, which would lead to a CO_2 emission burden several times higher than the direct use of fossil natural gas due to the fossil electricity generation.

As a result the use of fossil-generated electrical energy for CCU measures strongly jeopardises the achievement of climate protection targets and shall therefore be avoided [UBA 2016a]. A positive climate protection effect can only be achieved from a sufficiently low carbon dioxide load in the electricity used. For example, subject to economic viability, large-scale use of PtG plants to generate methane only makes sense in terms of the climate protection impact once the carbon dioxide content of the reference electricity is approx. 120 g CO_2eq/kWh [UBA 2016b]. The provisional value for 2018, however, is 468 g CO_2eq/kWh [UBA, 2020a]. The specific carbon dioxide content of the reference electricity or the substitution effect varies according to the CCU pathway. It depends on the fossil energy source to be substituted, the specific application and the energy efficiency of the individual technologies in the CCU measure (capture, products or energy sources provided, transport, etc.). From the avoided GHG emissions shown in Figure 6 it is possible to derive the GHG load of electricity used above for which it makes sense to integrate CCU technologies.

However, it is important to note that under certain conditions a CCU measure may have a climate protection impact for a short period of time in the transformation pathway towards a greenhouse gas neutral system, but this is positive impact vanishes in a fully renewable energy system. In light of long investment cycles and manifestation of process technologies some decades in advance, the connectivity of CCU measures to a greenhouse gas-neutral economy shall be ensured. For this reason, the primary goal of CO_2 avoidance in CCU measures should already be focused on in the transformation pathway.

Figure 7

Schematic representation of the climate protection impact with CCU



Note: *If the chemical industry increasingly produces renewable electricity-based carbon products, the waste energy source (currently with an average biogenic share of 50% for residual waste) will no longer fall into the "fossil carbon" category in the long term.

Source: [UBA 2019b]

The Figure 7 shows the above-mentioned relationships based on Figure 4 and Figure 5 in a schematic way.

5.4 Selected examples

5.4.1 Energy sector

Anthropogenic greenhouse gas emissions from the entire energy supply, including the provision of fuel, power and raw materials, can be completely avoided by switching to renewable energies [see, among others, UBA 2014, UBA 2016a, UBA 2016b, UBA 2019a, UBA 2019b]. At the same time efficiency potentials shall be raised across all areas of application in order to effectively enable the integration of renewable energies. Wherever technically possible, renewable energies should be used directly (see [UBA2014, UBA2016b, UBA2019a]). This is technically possible in the supply of electricity, space heating and in large parts of process heating and cooling, which means that CO_2 emissions can in principle be completely avoided. The security of supply of electricity can also be ensured by carbon-free energy storage, for example hydrogen. Accordingly, in the long term, carbon-based energy sources will be used in the energy industry to a much lesser extent than today. **In terms of the first test criterion, namely avoidance, fossil-fuelled energy-economy plants therefore do not represent an appropriate starting point for CCU measures.**

5.4.2 Steel industry

Both in Germany and worldwide, about six percent of total greenhouse gas emissions are caused by the steel industry. This is mainly caused by the blast furnace process, which is by far the most widespread process for iron and steel production based on primary raw materials (iron ore) and in which the use of hard coal coke is practically indispensable for process-engineering reasons. The carbon used leaves the blast furnace in the form of “blast furnace gas” on the one hand, and in dissolved form in the pig iron on the other hand, from which it is converted into the so-called “converter gas” in the steel converter with the help of injected oxygen. As it contains carbon monoxide, both blast furnace gas and converter gas are used for energy purposes in the steelworks itself in designated power plants or in other facilities. So ultimately the fossil carbon used – albeit in different places – is almost entirely emitted in the form of carbon dioxide.

Individual companies in the steel industry are promoting plans to reduce CO_2 emissions in the steel industry by separating CO or CO_2 from the resulting process gases and recycle them to a new use via CCU. However, this energy-intensive process would not reduce the emissions associated with steel-making because no new coke can be produced from the (fossil) carbon contained in the process gases and thus there would be no actual closing of the cycle, see chapter 5.1.2. So, despite CCU, just as much fossil coke would be used in the blast furnaces as before. The associated fossil CO_2 emissions would merely be shifted elsewhere via the use of the CCU products, but not avoided in the overall system.

There are other processes for iron and steel production based on primary raw materials with which CO_2 emissions from the blast furnace route can be more or less completely avoided. According to the latest state of knowledge, hydrogen-based direct reduction processes are the most advanced and already in industrial use; they have so far used natural gas and can be operated with hydrogen from renewable energies in the future. **Considering the release of fossil carbon dioxide in the blast furnace route and these practised alternatives, the application of CCU in the steel industry is not to be considered a suitable climate protection measure.**

5.4.3 Cement industry

The production of currently about 24 million tons of cement clinker and about 34 million tons of cement in Germany [VDZ 2020], directly released about 20 million tons of CO_2 from the raw materials and fuels [UBA 2020d]. These represent a share of around 2.5 per cent of the total emissions caused in Germany.

About two thirds of CO_2 emissions from the process are due to calcination, i.e. the thermal separation of CO_2 from limestone [UBA 2020e]. A reduction of these CO_2 emissions in production can be made possible through low-emission raw materials and the avoidance of process-related emissions by means of alternative building materials. However, they are currently still under development and research. A complete avoidance of CO_2 emissions from the cement industry would only be achievable by completely abandoning cement and concrete through substitution by other building materials, which seems unrealistic based on current judgement.

The CO_2 concentration in the exhaust gas of a cement rotary kiln can be increased from today's 14-30 per cent [VDZ 2013] to over 90 per cent in the exhaust gas stream by taking appropriate measures, e.g. the use of oxyfuel technology [VDZ 2013]. Accordingly exhaust gas with a high CO_2 concentration would be available so that relatively energy-efficient CO_2 capture of the carbon contained would be feasible. In accordance with the explanations in chapters 5.2 and 5.3 the use of captured carbon can, under certain boundary conditions, during a time-limited transition phase, result in fewer CO_2 emissions than the conventional fossil process. **A climate protection impact of CCU using raw material-related CO_2 from the cement industry in a fully renewable energy system is though not given** (see chapter 5.1.2). In light of the long investment cycles and manifestation of process technologies some decades in advance, the connectivity of CCU measures to a greenhouse gas-neutral economy shall be ensured. For this reason, the primary goal of CO_2 avoidance in CCU measures should already be focused in the transformation pathway.

The capture and processing of unavoidable concentrated CO_2 from waste gases produced by the cement industry should therefore not be pursued for climate protection reasons, but rather with a view to use as source of raw materials, see chapter 6.

5.5 Solutions for unavoidable raw material-related greenhouse gas emissions

As a result of the preceding assessment of CCU as a potential climate protection measure, it became clear that the use of fossil carbon – regardless of CCU measures – always leads to additional anthropogenic emissions in the end. Accordingly, no perspective solutions for greenhouse gas neutrality within industrial production can be shown for individual industrial applications, for example the cement, lime and glass industries. For these raw material-related or process-related greenhouse gas emissions it is important – through research and further development – to permanently

- avoid materials or products whose production is associated with unavoidable greenhouse gas emissions, or substitute them with less greenhouse gas-intensive materials and products, and
- avoid raw material-related or process-related emissions through fundamental process changes.

The objective shall be to find solutions for greenhouse gas neutrality within the originating productions or to reduce greenhouse gas emissions to a minimum.

As in the agricultural sector it can be assumed, based on current knowledge, that greenhouse gas emissions will not be completely avoidable on a long-term basis, even despite available technological development potential. **These greenhouse gas emissions can only be offset by permanently removing carbon from the atmosphere elsewhere ("carbon sinks"). The compensation of unavoidable greenhouse gas emissions from industrial and agricultural production must generally take place outside the actual originating impact area.**

However, this does not automatically mean the use of carbon capture and storage (CCS) techniques to store these CO_2 emissions. CCS is associated with several environmental risks [UBA 2015a], cannot guarantee safe and complete carbon storage according to current knowledge, has a low level of acceptance among the population and therefore does not represent a sustainable reduction option for greenhouse gas emissions in Germany.

Additional permanent carbon dioxide removal (CDR) can be achieved, for example, by securing and exploiting natural carbon sinks. These approaches are also physically limited in their national, European or global capacity and carry a risk of not being sustainable. Despite the need to reduce greenhouse gases via CDR measures, the associated conflicting goals and risks should be kept as low as possible [UBA 2019c]. Avoiding greenhouse gas emissions, by contrast, has generally priority. By strengthening and securing natural carbon sinks, synergies with other environmental challenges, such as biodiversity, can be addressed at the same time.

The RESCUE study (UBA 2019a, b, c) shows that the unavoidable greenhouse gas emissions from industrial processes, agriculture, waste and wastewater can be fully compensated by natural carbon sinks and sustainable forest management and that CCS is not required to achieve greenhouse gas neutrality. In the most ambitious green scenarios presented there (GreenSupreme, GreenLife and GreenMe), net zero emissions can be safely achieved by 2050.

Linking CDR measures that promise long-lasting safe carbon or carbon dioxide sequestration or storage to the emitting GHG emitters can be organised, for example, through new market mechanisms (national, European or global carbon markets, financing projects) of the Paris Agreement. Specific considerations in this respect as well as on the requirements for long-lasting secure carbon or carbon dioxide sequestration or storage, have so far been limited in scientific and political debates. However, they are urgently needed on a medium-term basis in order to provide these areas with appropriate perspectives well.

Irrespective of the above, an important contribution to climate protection shall also be made in industrial applications with unavoidable emissions, as in all other industrial production areas, by

- increasing energy efficiency using energy-efficient techniques, optimising procedures and processes, and consistently using waste heat, as well as
- switching completely to renewable energy sources and, where technically possible, to the direct use of renewable electricity.

Excursus 2: Cement industry – Integrating carbon dioxide into a product

The unavoidable, raw material-related CO_2 emissions of the cement industry must not lead to an increase in the CO_2 concentration of the atmosphere in the long term. Instead carbon shall be permanently bound to the same extent. The compensation of unavoidable CO_2 emissions from the cement industry can also take place outside the actual causative impact area. The recarbonisation of concrete is also currently being discussed [Sacchi et al. 2020]. This option is currently not well-tested and the actual potential is not yet clear. The research and development of sustainable and preferably natural sinks is currently one of the most urgent research issues to compensate for unavoidable greenhouse gas emissions.

6. CCU as a raw material source

Carbon-based energy carriers and carbon based products are practically indispensable in life. Even if avoidance potentials are fully raised on the way to a sustainable society and can largely be dispensed with in the energy industry in particular, a raw material demand for carbon will continue to exist in the future for the provision of energy sources and products. In contrast to the current situation, future developments shall be oriented towards avoiding emission of this carbon into the atmosphere after use, but rather – as far as possible – continuing to use it with as little energy loss in the system as possible.

6.1 Demand for carbon as a raw material

Currently large shares of the chemical industry's raw material supply in Germany are based on fossil carbon sources (such as mineral oil, natural gas and coal), which are processed into organic basic chemicals and downstream products. In order to replace them, these carbon feedstock shall also become greenhouse gas neutral, as otherwise anthropogenic CO_2 emissions at the end of the product's life will continue to increase the greenhouse effect (see chapter 5.1.2 and Figure 5). Since carbon continues to be a necessary raw material in the chemical industry, it is not possible to speak of "decarbonisation" in the literal sense, which is the appropriate term in almost all other sectors of the economy. The change of carbon source may alternatively be better expressed by the term "defossilisation".

The demand for carbon-containing products is characterised in the following by the mass fraction of carbon. This makes it possible to compare different sources and simplifies the allocation in the following chapter, insofar as carbon dioxide shall be used as a carbon source.[11]

The current annual use of fossil raw materials in the chemical industry in Germany is – depending on the publication – little over 20 million tons of carbon. Only a very small part of this is already covered directly from CO_2 at present (e.g. urea, a few polyol processes). In fact, carbon currently originates from fossil raw materials. A major consideration in the provision of carbon for the chemical industry is the associated energy demand. Today's fossil feedstock contains high amounts of stored energy that is used in the processes. Future raw materials such as carbon dioxide contain little internal energy. This energy must be provided in the defossilised manufacturing pathways of future products. In addition to energy use, other environmental impacts that will occur alongside global warming (e.g. eutrophication, acidification or the release of toxic substances [UBA 2020b]). These play a significant role in the assessment of future manufacturing pathways. For economic reasons alone, the most energy-efficient way to provide such raw materials will always be chosen, unless other environmental impacts militate against it. **The provision of carbon from CCU does not belong to the energy-efficient carbon provision pathways.**

Besides chemical industry, carbon-based fuels will also be needed in the long term for various applications, including aviation and maritime transport. Under the premise of avoidance, renewable electricity is used directly wherever this is technically possible, with the result, that the need for fuel and combustibles is significantly reduced compared to the present day.[12] Scenarios from various publications provide an orientation as to whether and to what extent the remaining demand for fuel will be produced in Germany and what demand for CO_2 shall be provided for this production in this country. The RESCUE study [UBA 2019b] assumes a carbon demand for the entire fuel, power and raw material supply of between 8 million and 40 million tons of carbon (converted from 30 million to 148 million tons of CO_2) per year, depending on the scenario. However, a specific forecast of what will be produced and where

11 One ton of carbon is equivalent to 3.664 tons of carbon dioxide. This conversion is used as the basis for the calculations in this paper, even though these stoichiometric ratios cannot always be achieved in real plants due to technical efficiencies.

12 In the RESCUE study, fuel demand in 2050 is reduced by around 65 per cent in GreenSupreme and by around 30 per cent in GreenLate compared to 2015.

Excursus 3: Comparison of different raw material routes

When considering energy efficiency in the provision of raw materials, for example, mechanical recycling, e.g. of packaging waste, is more efficient than chemical recycling. The basis of the comparison shall be an identical benefit. If, however, a product from mechanical recycling requires more raw material than a product of the same use from chemical recycling, it becomes clear that the assessment of energy efficiency alone is not sufficient.

Along with the efficient use of energy, the raw material intensity (amount of raw material used per product) shall be taken into account. Only such processes are to be considered that can demonstrate the highest possible energy efficiency and at the same time a low raw material intensity.

is difficult to foresee against the background of the many influencing factors and global developments. In Figure 8 the pathways that will continue to have carbon feedstock demand are shown on the right.

The total carbon demand in Germany will very likely not fall below 20 million tons of carbon, even considering strong saving potentials, and could also reach orders of magnitude around 40 million tons of carbon in the worst case.

6.2 Availability of carbon as a source of raw materials

If products are unavoidable, carbon will also be needed in the long term to provide them. The most energy-efficient measures for the provision of carbon are generally those that require the fewest (chemical) conversions. Figure 8 displays the provisioning pathways on the left-hand side.

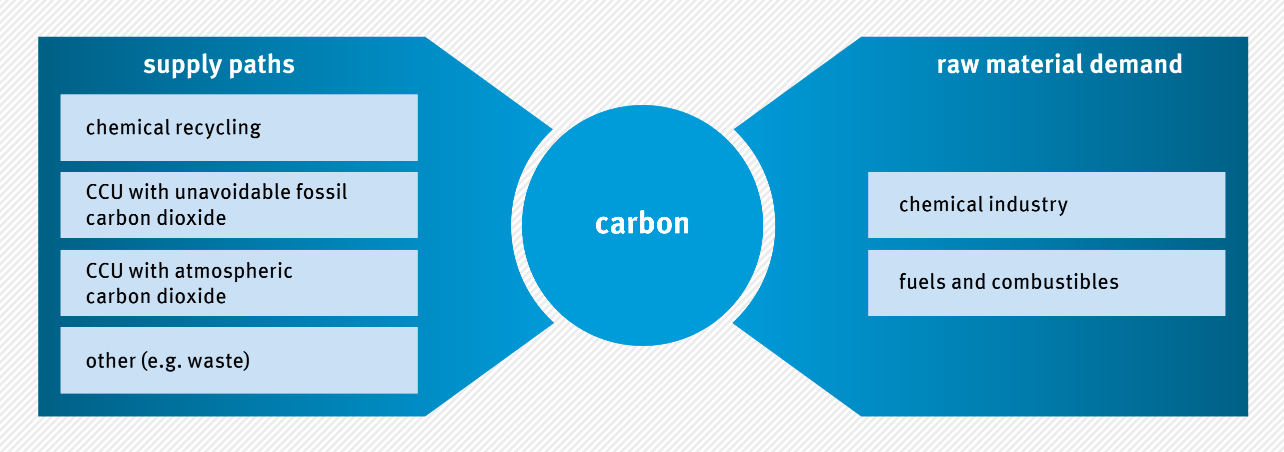
Recycling of carbon contained in plastic waste: Alongside other carbon-containing waste materials, the chemical recycling of plastic waste can probably be used as an energy- and material-efficient source of carbon, although current technical developments do not yet allow us to foresee how much of the theoretical potential will actually become usable. From the roadmap by FutureCamp and DECHEMA [FutureCamp 2019], an amount of just over 2 million tons of pure carbon can be calculated, which the authors consider to be the potential from plastic waste. Accordingly, only a small share of the long-term demand of carbon can be covered from this.

Other approaches (e.g. sustainable residual biomass, other wastes) are also conceivable, whose sustainable contribution to the provision of carbon cannot be clearly estimated and will not be addressed in more detail here.

CO_2 as a carbon source: From today's point of view carbon dioxide will continue to be a necessary source of carbon in the future, when all other more energy-efficient pathways for providing carbon have been fully used. From the demand quantity presented in chapter 6.1 and the previously presented small quantities of direct recycling potentials foreseeable so far, it becomes clear that there will probably be a large gap. **This gap between carbon demand and possible coverage by other carbon supply pathways will have to be covered by CCU measures, despite their high energy demand.**

Figure 8

Overview of carbon demand and supply pathways



Source: German Environment Agency

CO_2 from sources in which it occurs in high concentrations (e.g. in plants with oxyfuel processes) can be made usable with less energy consumption compared to low-concentration CO_2 (e.g. from the atmosphere). However, the required amount of renewable energy is not necessarily available at the site of a CO_2-emitting plant.

As already shown in chapter 5, unavoidable greenhouse gas emissions are left in some industrial processes. Out of this, slightly more than 5 million tons of carbon from lime, cement and glass industries could annually be made available for CCU measures[13] (20 million tons of carbon dioxide).

Regardless of whether biogenic carbon is directly available for feedstock applications, an efficient use of biogenic residues shall be strived for so that, for example, biogas plants or sewage gas plants can also be used in future as a point source of carbon dioxide. Biogas production from liquid manure or biowaste generates substantial amounts of CO_2 which might be captured making biomethane production even more efficient. Depending on the process used, this captured CO_2 has high purity and is thus a potentially favourable input for CCU measures. Waste as an energy source, e.g. mixed municipal and commercial waste, is containing a large biogenic carbon fraction that – after incineration – can be used as a CO_2 point source and used for CCU measures.

These and other unavoidable industrial point sources will not be sufficient to fully cover the raw material demand. This results in the need to also provide carbon as feedstock directly from atmospheric carbon dioxide.

The energy required to produce high-value products (e.g. a assortment of methane, propane and methanol) from 100 million tons of carbon dioxide is about 1,000 terawatt hours (TWh) for the chemical reactions alone. The effort of capturing or separating CO_2 and transporting it need to be added to this. This would correspond to about twice the current annual consumption of electrical energy in Germany (2018: 513 TWh [UBA 2020a]). The availability of CO_2 as a raw material is not a carbon but an energy problem.

13 The various scenarios in RESCUE [UBA 2019b] show between 8.1 million and 18.7 million tons of remaining CO_2 emissions from lime, cement and glass production.

6.3 The role of CCUs in a national sustainable energy system

In the course of energy transition and integration of new energy and electricity consumers, such as electromobility, power to heat and others, a further, substantial expansion of renewable energies is required in Germany. The future electricity supply will be significantly higher than today's level despite energy efficiency measures.[14] In particular, the low-cost and high-yield sites for renewable energies are being developed. Assuming high efficiency potentials, the RESCUE study assumes more than a doubling of onshore wind energy, about a tripling of photovoltaic capacity and roughly a fivefold increase in wind off-shore capacities in Germany [UBA 2019b]. Depending on the scenario of the RESCUE study, electricity generation in Germany is in the order of 750 to over 900 TWh in 2050 (2018: 513 TWh [UBA 2020a]). Other long-term studies[15] have reached comparable results. In the long term an import of PtG/PtL/PtS products is postulated as the result of optimising processes in the energy sector. The reason for this situation is that national sites for renewable energies are not competitive in comparison to a large number of international sites for renewable electricity generation due to relatively low full load hours. **Not the issue of carbon availability but the cost of energy expenditure will be decisive for the location and deployment of CCU measures.**

The conclusions from chapter 5 and 6 referred to the demand for energy in the CCU measures and the associated need to avoid carbon-based energy sources and products as far as possible. The differences that may otherwise arise are made clear in UBA's RESCUE study [UBA 2019b]. In the GreenSupreme scenario, in which electricity is also used directly where technically possible, renewables-based net electricity generation[16] of around 850 TWh is required. In the GreenLate scenario in which hydrocarbons are increasingly used although renewable electricity could also be directly deployed, around 2,700 TWh of renewable electricity is required per year.

In addition to the question on the amount of energy required and the ways of providing carbon (import of CCU-PtG/-PtL/-PtS products CO_2 transport within Germany from industrial point sources, etc.), further energy-economic aspects shall be considered when integrating CCU measures. In an energy system that is increasingly based on fluctuating renewable energies, making electricity demand more flexible is an efficient and economic measure. This serves to reduce the necessary minimum generation from conventional power plants in transitional periods, to limit the demand for renewable power generation plants and at the same time to maintain a high level of system stability. With this in mind, requirements shall also be made for the integration of new energy consumers[17].

In the RESCUE study of the UBA [UBA 2019b], a very ambitious scenario (GreenSupreme) results in an energetic production potential of up to 100 TWh PtG/PtL/PtS products per year in Germany.[18] This could be accompanied by the use of around 20 million tons of carbon dioxide from industrial point sources through expedient site linkages.[19] If energy efficiency measures and the fuel switch to electricity-based technologies are not consistently implemented across all fields of applications, it can be assumed following GreenLate[20] that there is no energetic potential for CCU measures in Germany. The economic viability of CCU measures with PtG/PtL/PtS plants in Germany as part of energy supply thus appears to be limited in the long term.

14 See for example [BDI 2018, DENA 2018, Öko-Institut (Institute for Applied Ecology) 2015] or [UBA2014; 2019].
15 For example from [BDI 2018, DENA 2018, Öko-Institut (Institute for Applied Ecology) 2015] or [UBA2014; 2019].
16 Net electricity generation includes the provision of all electricity required for the supply of fuel, power and raw materials as well as grid losses during the transport of electricity. It includes electricity used both directly as final energy and as a secondary energy source in PtG/PtL/PtS plants.
17 And have already been addressed, for example, in the CHP Act, especially in innovative CHP.
18 Using around 150 TWh of renewable electricity for their production.
19 Around 8 million tons of carbon dioxide remain in GreenSupreme from cement, lime and glass production.
20 Assuming further that hydrogen becomes established as a fuel.

6.4 Selected examples

6.4.1 Chemical industry

A characteristic of the chemical industry is the high diversity of products and production processes as well as installations. A comprehensive overview of the possibilities of using carbon dioxide as feedstock is therefore not possible in this context, but a few possibilities for using carbon dioxide will be presented as examples.

Production of alkenes/olefins: Alkenes (also called olefins) are unsaturated hydrocarbons with contain a carbon double bond. The two most commonly used representatives are ethene (ethylene) and propene (propylene), which are the most important basic chemicals in organic chemistry. They are used to make plastics, alcohols and detergent ingredients, for example. Nowadays the usual production is done by cracking fossil long-chain hydrocarbons (especially naphtha) in steam crackers. A number of approaches are conceivable to defossilise these important bulk products of organic chemistry.

On the one hand the existing structure of organic basic chemical production sites might be largely maintained while the supply is shifted to non-fossil PtL products. Additional energy-related emissions should than be avoided through extensive electrification, e.g. of the crackers. The PtL raw materials would then be hydrocarbon mixtures produced by Fischer-Tropsch synthesis, for example.

On the other hand alkenes could be produced from methanol for example. The latter can be synthesised as a platform chemical from hydrogen and carbon dioxide produced in a greenhouse gas-neutral way. A variety of other products can be produced from methanol, e.g. formaldehyde, long-chain fuels and fuel additives.

Furthermore research is carried out on other production routes, for example, to enable the direct, electrochemical synthesis of products (e.g. alkenes and methanol).

Regardless of the processes outlined that are possible in a renewable system in the future, it is clear that the carbon demand for olefins can be met via CCU measures.

Production of urea: One example of direct carbon dioxide use is the large-scale production of urea, which is used as a raw material for fertilisers, among other applications. For this purpose, ammonia (NH3) from the Haber-Bosch synthesis is converted with carbon dioxide via the intermediate product ammonium carbamate to urea (and water). Currently hydrogen for ammonia synthesis and high-purity carbon dioxide are produced by steam reforming of fossil natural gas. By switching to water electrolysis in combination with renewable electricity, the generation of carbon dioxide is thus avoided. Carbon dioxide required for urea synthesis can be provided from CCU measures in the future. To produce today's quantities of urea, 0.38 million tons of carbon dioxide are needed in Germany every year.

6.4.2 Cement industry

In the cement industry, raw material-related carbon dioxide emissions remain unavoidable, when cement is produced using current techniques (cf. Chapter 5.4.3). The preceding illustrations and specific examples in chapter 5.5 show that there is a demand for carbon in the long term, and that it must be met. Flue gas from the cement industry can therefore be an option for covering carbon demand. Due to the high concentrations of carbon dioxide in flue gases (up to more than 90 per cent in combination with oxyfuel), this is a comparatively efficient option with low energy requirements for carbon supply. According to UBA scenario calculations, between 5 million and 14.5 million tons of carbon dioxide will still be produced by the German cement industry in 2050 [UBA2019b].

Other production processes such as the lime and glass industries, with their unavoidable raw material-related carbon dioxide emissions, can also contribute to meeting the carbon demand where appropriate.

List of figures

List of abbreviations

CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
DAC	Direct Air Capture
CDR	Carbon Dioxide Removal
EOR	Enhanced Oil Recovery
PtC	Power to Chemical
PtG	Power to Gas
PtL	Power to Liquid
PtS	Power to Solid
PtX	Power to X
PA	Paris Agreement

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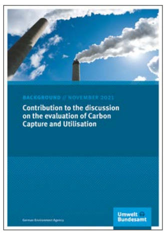

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