Carbon Dioxide Removal in the Industry of North Rhine-Westphalia

Discussion paper of the Carbon Economy Working Group

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Authors:
Dr. Christoph Glasner
(Fraunhofer UMSICHT)
Dr. Iris Rieth-Menze
(IN4climate.NRW)
Prof. Dr. Ulrich Seifert
(Fraunhofer UMSICHT)
Domenik Treß
(IN4climate.NRW)
Christoph Zeiss
(Wuppertal Institute)

Contact & Coordination:
Domenik Treß (IN4climate.NRW),
Expert in industry and production,
CarbonManagement@energy4climate.nrw

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Core messages

Carbon Dioxide Removal (CDR) is not a distant vision for the future, but an opportunity for **existing industrial processes** in North Rhine-Westphalia (NRW). **Synergies** exist between carbon management in industry and the possibility of producing **permanent** negative emissions based on shared infrastructure (Chapter 2). Emission reduction and technical CO_2 sinks go hand in hand here.

BioCCS processes (biogenic carbon capture and storage) offer relevant potential for industrial negative emissions in NRW. In applications in which **biogenic waste is used to generate energy** (including biogas processing and paper, sugar or alcohol production), particularly **in synergy with processes involving unavoidable CO_2 formation** (e.g. cement, lime and chemical industry as well as waste incineration), BioCCS can contribute to greenhouse gas neutrality.

For the mechanical and plant engineering industry in North Rhine-Westphalia, **Direct Air Capture (DAC)** offers great potential for value creation as a rapidly growing export market of the future. However, the application of DAC in NRW is likely to remain rather limited. On the one hand, the additional renewable energy required for this in the coming decades will be urgently needed in other areas as part of the transformation to greenhouse gas neutrality. On the other hand, there are numerous locations worldwide that have more favourable conditions and are therefore better suited for DAC.

The upscaling of carbon dioxide removal technologies has limited potential and therefore requires a **broad-ranging technology portfolio** to minimise risks. The approaches outlined here for industrial BioCCS are a sensible, feasible and targeted starting point for the ramp-up of permanent CDR methods in North Rhine-Westphalia. At the same time, there are conflicting goals and risks (Chapter 3) that need to be kept in mind. It is therefore important that the main focus remains on avoiding CO_2 emissions (Chapter 1), while at the same time strengthening natural sinks and driving forward research and development of further CDR technologies. These measures must be implemented simultaneously and complement each other, which is why it is not enough to focus on just one or a few selected technologies.

To achieve the synergies for CDR outlined in this publication and to implement them in specific investment decisions, **a clear perspective for industrial CDR technologies is urgently needed.** The framework conditions for this are currently lacking. Furthermore, it is important to take future quantities of negative emissions into account already today when dimensioning the separation plants and the transport and storage infrastructures (Chapter 4).

1 Carbon Dioxide Removal (CDR): What is it about?

1.1 Unavoidable and hard-to-abate residual emissions

North Rhine-Westphalia has committed itself to being greenhouse gas neutral by 2045 through its climate protection law. The so-called hard-to-abate residual emissions are among the particular challenges on the way to greenhouse gas neutrality. These are likely to occur, for example, in land use and agriculture, but also in certain industrial processes.

In this context, residual emissions are defined as the **amount of greenhouse gas emissions**[1] **that actually enter the atmosphere** in and after the net-zero year 2045 (Schenuit et al. 2023). To achieve net-zero emissions, the removal of CO_2 from the atmosphere must be at least equivalent to the amount of greenhouse gases added to the atmosphere. As such, residual emissions usually require a justification as to why they cannot be avoided (Brad et al. 2024). While residual emissions initially represent only a number, the question of whether they are considered „unavoidable" or „difficult to avoid" is much more difficult to answer. The availability of options for avoiding greenhouse gas emissions is subject to change over time and is driven by continuous research and development, so that greenhouse gas emissions that are unavoidable today may be avoidable in the future under more advanced framework conditions.

Depending on the uncertainty regarding which residual emissions will actually be unavoidable in ten or twenty years, there are different scenarios with different amounts of residual emissions (see Table 1). The Intergovernmental Panel on Climate Change (IPCC) (2023) makes it clear that greenhouse gas neutrality – and thus the stabilisation of global temperatures – is only possible if residual emissions are offset by Carbon Dioxide Removal (CDR)[2].

1.2 Carbon Dioxide Removal: Basic classification

Carbon Dioxide Removal (CDR) is defined as **human activity that captures CO_2 from the atmosphere and stores it for decades to millennia** (Smith et al. 2024, p. 23), i.e. for climatically relevant periods. These extracted quantities of CO_2 are also referred to as negative emissions. For North Rhine-Westphalia to achieve its goal of net greenhouse gas neutrality, at least as much CO_2 must be removed from the atmosphere by 2045 as the remaining greenhouse gas sources continue to emit[3]. Carbon Dioxide Removal will have to offset not only residual CO_2 emissions but also the climate impact of other greenhouse gas emissions such as methane and nitrous oxide, because the goal is comprehensive greenhouse gas neutrality, not just CO_2 neutrality. Net zero CO_2 emissions will therefore have to be achieved before 2045 in order to achieve greenhouse gas neutrality in 2045, taking into account all greenhouse gases (Reisinger und Geden 2023). In addition, the German Climate Change Act (Section 3 (2)) and the European Climate Law specify that greenhouse gas emissions must be net negative for the period after 2050. This long-term goal of net negative emissions –more CO_2 is captured from the atmosphere and permanently stored than is released as greenhouse gases over the same period – is currently being defined and developed in more detail by the German government in the „Long-Term Strategy for Negative Emissions to Deal with Unavoidable Residual Emissions (LNe)".

1 The term "greenhouse gas emissions" in the narrower sense refers to the release of greenhouse gases into the atmosphere, as it is used in this document. Occasionally, the term is also used imprecisely for the formation of greenhouse gases without release into the atmosphere.

2 See IPCC AR6, Working Group III, Summary for Policymakers, C.11.

3 In equivalents.

In its Carbon Removals and Carbon Farming Regulation (CRCF)[4], the European Union distinguishes between three categories for certification: 1) carbon farming, 2) carbon storage in products and 3) permanent carbon removals (European Commission 2024a).

The first category, carbon farming, relates to natural sinks and thus the LULUCF sector (land use, land use changes and forestry). It involves a variety of ways to **additionally** and **durably** increase the carbon sequestration in soils and ecosystems.

The category of carbon storage in products refers to particularly long-lasting bioeconomy products. In line with the above definition of CDR, the storage period is at least several decades. In the CRCF certification framework, this category initially includes only bio-based materials in the construction sector due to the long product life.

These must be distinguished from products that permanently chemically bind atmospheric CO_2 captured by carbon capture facilities, because these are categorised as „permanent carbon removal" in the third category for regulatory purposes. If captured CO_2 is permanently bound in products, this is also referred to as „CCUS" (Carbon Dioxide Capture, Utilisation and Storage)[5]. By contrast, „CCU" (carbon capture and utilisation) generally describes the use of captured carbon dioxide, regardless of the source and duration of storage in the product. Many CCU products, such as fuels, do not result in permanent storage, but ultimately in delayed emissions. CCU without permanent sequestration in a product thus does not contribute to negative emissions, but is rather a way to use carbon multiple times and thereby avoid additional carbon input in the form of fossil carbon carriers (Gabrielli et al. 2020).

4 Full name: Certification Framework for permanent carbon removals, carbon farming and carbon storage in products.

5 "CCUS" is also often used as a collective term for CCU and CCS. However, this leads to a mixing of these partially very different approaches. The use of the abbreviation "CCUS" for utilisation and storage in the product follows DIN SPEC 91458.

The third category in the EU CRCF covers the permanent storage of **atmospheric** CO_2 in geological formations and the **permanent** chemical sequestration of **atmospheric** CO_2 in certain products.[6] Permanent carbon removals can be achieved with the help of the central technology of carbon capture and storage (CCS), whereby CO_2 is stored deep underground. This is done to generate negative emissions on the basis of direct air capture from the ambient air (DACCS) or by storing biogenic CO_2 (BioCCS, or previously often called BECCS[7]). The advantage of this category lies in the permanence of the storage (Chiquier et al. 2022). If adequately developed, geological storage is possible for many centuries, with the CO_2 gradually being mineralised and thus permanently removed from the atmosphere (CDRmare 2024). Permanent storage in products refers to a list of specific products to be defined by the EU, which do not release the CO_2 again at the end of their product life because they are not incinerated but landfilled. These are essentially carbonated, mineral construction products.[8]

6 See draft of the European Commission's delegated regulation on permanent CCU, Ares(2024)4402362.

7 The term "BioCCS" was introduced in the EU Commission's Industrial Carbon Management Strategy and describes the capture and permanent storage of biogenic CO_2 at energy plants or industrial processes (European Commission 2024b). "BioCCS" therefore not only refers to biogenic CO_2 that is produced during combustion processes for energy generation ("BECCS"), but also includes process-related biogenic CO_2 that does not originate from processes in which energy generation is the primary objective.

8 See draft of the European Commission's delegated regulation on permanent CCU, Ares(2024)4402362.

In this discussion paper, we will focus on the permanent CDR potentials for North Rhine-Westphalia's industry that may arise from the upscaling of carbon management. Non-permanent ways of CO_2 removal via natural sinks (i.e. in the first category „carbon farming") and bioeconomic building materials (the second category) are not considered. Natural sinks are nevertheless not of less importance, since the binding of CO_2 in the form of carbon in ecosystems is already possible today and, compared to technical sinks, is relatively inexpensive and offers many other co-benefits. Expanding natural sinks is not only crucial for climate protection, but also supports climate change adaptation, nature conservation and biodiversity. Technical and natural sinks are therefore strategies that complement each other, because with natural sinks there is a steadily increasing risk as climate change progresses that the CO_2 will not remain permanently bound (Chiquier et al. 2022). Droughts and the associated fires can release the CO_2 directly back into the atmosphere. Other uncertainties include possible changes in land use within the next century and the associated re-release of CO_2. For this reason, the additional development of permanent technical sinks is a crucial measure to ensure with the greatest possible certainty that the CO_2 removed from the atmosphere remains stored permanently. Monitoring, reporting and verification must be designed to ensure the permanence of storage and clearly regulate liability in the event that CO_2 is released again (Schuett 2024).

1.3 The role of CDR in an industrial carbon management hierarchy

Over the next two decades, the top priority for achieving greenhouse gas neutrality in industry remains minimising CO_2 emissions as much as possible. Various abatement strategies are available in all sectors and need to be implemented in a prioritised and synergetic way. Examples include the rapid expansion of renewable energies, the conversion of industrial processes to hydrogen or direct electrification, efficiency improvements and the increasing circular economy. Carbon Dioxide Removal is only effective if the available abatement strategies are fully exploited. According to scientific climate scenarios, it will be challenging enough to expand technical and natural sinks to such an extent that they can provide negative emissions in the range of hard-to-abate residual emissions in 2045. For the largest share of CO_2, it generally makes more sense, both technically and economically, to ensure that its formation is avoided.

With regard to the role of Carbon Dioxide Removal as part of Carbon Management[9] the following prioritisation is helpful:

9 Carbon management describes how carbon itself is handled (MWIDE 2021). Apart from CO_2 management (i.e. carbon capture and X), this primarily involves using less carbon and substituting fossil carbon sources with sustainable ones. In contrast, the German government's Carbon Management Strategy uses a narrower definition to address only the aspect of CO_2 management, with avoidance and substitution being identified as the preferred options but not explored in detail. This paper is based on the broader definition set out in the Carbon Management Strategy of the state of North Rhine-Westphalia.

An industrial carbon management hierarchy

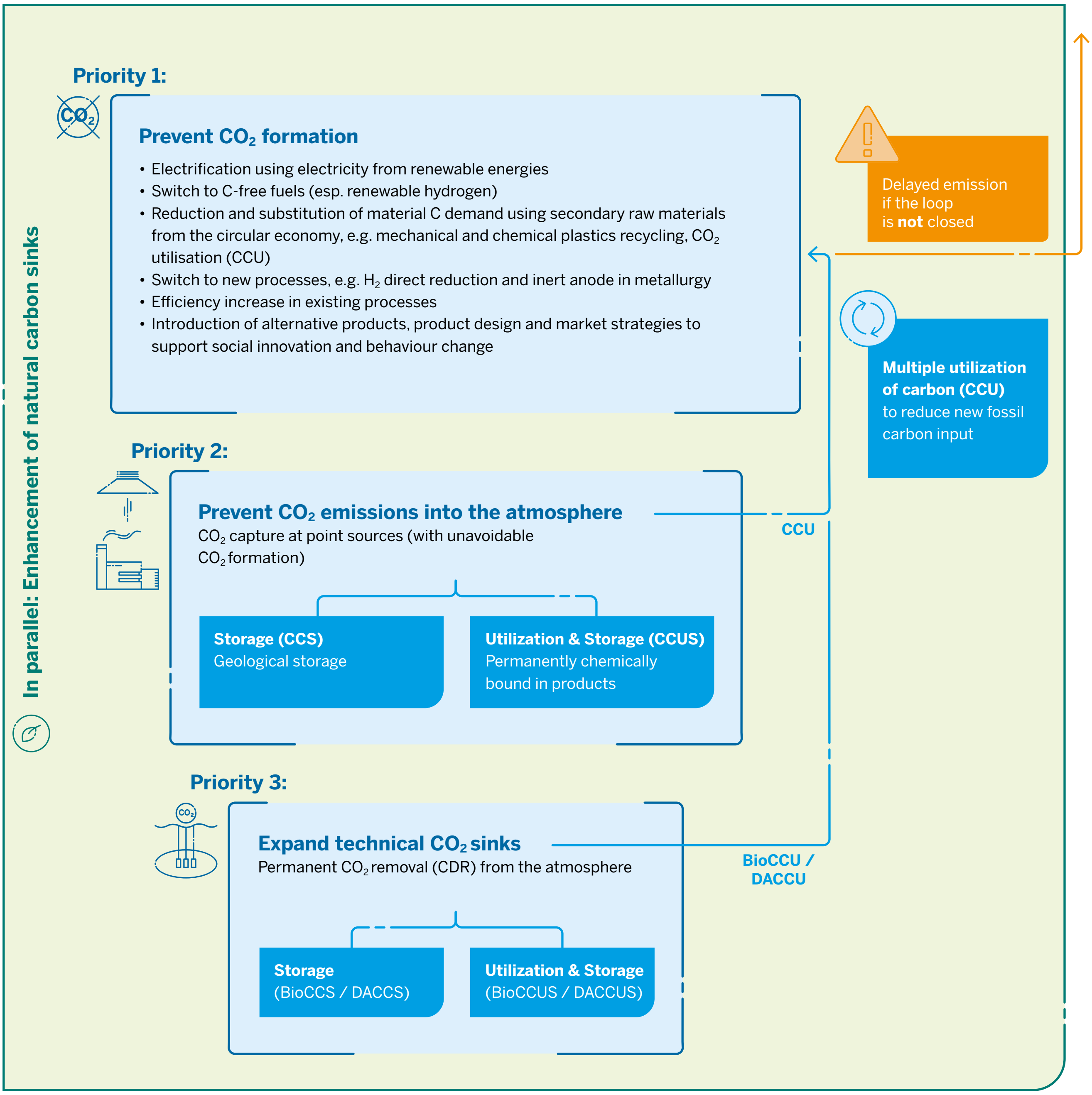

Figure 1: Prioritisation of the various options for action on the path to greenhouse gas neutrality without implication of a chronological sequence.

Priority 1: Prevent CO_2 formation

Measures to avoid the formation of CO_2 are currently of the greatest strategic relevance. The options displayed in the figure contribute in different ways to reducing or even avoiding the formation of CO_2, thus eliminating the need for costly and laborious capture and storage.

Priority 2: Prevent CO_2 emissions into the atmosphere

In cases where CO_2 formation cannot be avoided (e.g. process-related CO_2 quantities in cement or lime production), the CO_2 generated should be captured and stored to the greatest extent possible in order to prevent emissions into the atmosphere. There are two ways of storing CO_2 permanently: in deep geological formations (CCS) or by permanently storing it in products (CCUS)[10]. A third option is the non-permanent storage of the captured CO_2 in products with a limited useful life (carbon capture and usage, CCU). By capturing CO_2 and incorporating its carbon into products, emissions are avoided as long as the product does not decompose. Nevertheless, by using captured CO_2 as a raw material for production, primary fossil carbon compounds are replaced and the input of additional fossil carbon into the overall system is avoided. Depending on the product, however, even multiple use of the captured CO_2 cannot prevent end-of-life emissions, albeit with a time lag. Therefore, products that are CCU-based or otherwise made from recycled carbon do not, as a rule, serve as a permanent technical sink. At the same time, CCU is a constructive component of carbon management when the source is considered rather than the sink. The main objective of CCU is to make carbon available for production again and thus to reduce the input of additional fossil carbon into the technosphere – in contrast to permanent storage processes (CCS, CCUS), which serve to permanently remove carbon from the system (technosphere and atmosphere).

Priority 3: Expand technical CO_2 sinks

CO_2 capture technologies cannot achieve 100 per cent capture rates. For this reason, and also because there will always be residual greenhouse gas emissions from other sectors, residual emissions will remain despite the capture of CO_2 at industrial point sources. These residual emissions can and must be offset by Carbon Dioxide Removal (CDR) from the atmosphere. The permanent storage options for industrial CDR are essentially the same as for CCS and CCUS in general. However, CDR involves the storage of atmospheric CO_2, which is captured either directly (DACCS/DACCUS) or indirectly by capturing biogenic CO_2 from industrial (BioCCS/BioCCUS). Biogenic CO_2 was previously removed from the atmosphere by means of photosynthesis.

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10 „CCUS“ is also often used as a collective term for CCU and CCS. However, this leads to a conflation of these partially very different approaches. The use of the abbreviation “CCUS” for capturing and storage in the product is in line with DIN SPEC 91458.

	Prognos et al. (2021)	Ariadne (2023)	BDI (2021)	dena (2021)	SCI4climate.NRW (2023)	T45-scenarios (2024)
Residual emissions in million tonnes of CO_2 equivalents	63	62–127	59	87	55	55

Table 1: Residual emissions in Germany in 2045 according to various climate neutrality studies (Prognos et al. 2021, BCG 2021, dena 2021, SCI4climate.NRW 2023, T45-Langfristszenarien in Fraunhofer ISI et al. 2024 und Ariadne in Merfort et al. 2023)

Residual emissions across Germany will amount to at least 55 million tonnes of CO_2 equivalents in 2045 (see Table 1) compared to 674 million tonnes of CO_2 equivalents in total emissions in 2023. It will be a major challenge to achieve even a double-digit million amount of negative emissions in the next two decades. The principle that emerges from this is that the lower the residual emissions and the faster the pace of emissions reduction, the more likely it is that Germany will achieve net zero emissions or even net negative emissions by mid-century (Minx et al. 2018). Carbon Dioxide Removal cannot, therefore, be a substitute for emissions reduction. On the contrary, it is only through ambitious emissions reduction that CDR can play a relevant role on the road to climate neutrality.

At the same time, the carbon management hierarchy should not be understood in a temporal sense. It is important to start preparing and building CO_2 infrastructure as early as possible so that CCU/CCS technologies can play a relevant role in the 2030s and enable CDR via this technology pathway. This is the only realistic way to achieve sufficient scaling of the technical sinks to achieve greenhouse gas neutrality (Lamb et al. 2024). Furthermore, the mechanical and plant engineering industry in North Rhine-Westphalia now has the opportunity to tap into value creation potential to serve the global future market for negative emission technologies.

2 Potential for permanent CDR in NRW industry

There are still no clear framework conditions for carbon dioxide removal, but they are currently being successively developed at the European Union level. For the future scenario described in this chapter, we assume that an EU mechanism for negative emissions will have been developed by the end of the 2020s that offers an appropriate price as an incentive for each tonne of CO_2 permanently removed from the atmosphere.

The following chapter is therefore not about the detailed questions of regulation that need to be clarified by then, but rather about outlining how industry in North Rhine-Westphalia can generate negative emissions in the future. This vision of the future is based on workshops held by the state initiative IN4climate.NRW and is intended to serve as an aspirational scenario that highlights the potential once framework conditions and incentives have been put in place. It has also been compared with published political strategies and their key points at the federal and EU level (as of June 2024). The vision of the future is written as a „backcast", i.e. looking out from an imagined future in 2045.

2.1 Outline of a permanent CDR in NRW industry in the future

Let's imagine we are in the year 2045, the target year for a greenhouse gas-neutral North Rhine-Westphalia. This vision of the future is based on climate neutrality scenarios[11] as well as political goals and strategies and is optimistic in its approach. In the decades before, processes with avoidable CO_2 formation were converted to CO_2-neutral technologies such as electrification or green hydrogen. Almost all processes in the primary industry with unavoidable or hard-to-abate CO_2 formation, as well as waste incineration plants, were equipped with CO_2 capture facilities. This means that the potential of the first two priority levels of the carbon management hierarchy presented here (Fig. 1) has been largely exhausted and the other pieces of the puzzle to achieve greenhouse gas neutrality, such as renewable energies, storage capacities, sector coupling, circular economy, sufficiency, etc., have been successfully scaled. The remaining carbon demand is covered by sustainable carbon sources in a climate-neutral way. In this context, regional residues and waste biomasses play an important role in the raw material supply of carbon-based industries such as the chemical industry.

In this scenario, negative emissions are generated in synergy with industrial production processes at sites connected to a CO_2 transport infrastructure, helping to offset residual emissions. These are mainly industrial processes in which (proportionate) biogenic CO_2 is captured using carbon capture technologies and then permanently stored (BioCCS).

BioCCS is therefore implemented in North Rhine-Westphalia's industry in synergy with the plants in which biomass is used or CO_2 is captured anyway. Plants for capturing process-related and unavoidable CO_2 amounts are designed in such a way that biogenic CO_2 amounts are also captured. The CO_2 removal is therefore achieved proportionately, using the same systems that are used to prevent process emissions. The negative emissions generated in this way initially compensate for the remaining emissions from the firing process, since the capture rate does not reach 100 per cent. Quantities in excess of this can even generate additional income through the sale of negative emissions certificates and thus provide an incentive to achieve the highest possible capture rate when dimensioning a capture system. In North Rhine-Westphalia, BioCCS is therefore primarily implemented by industry. By contrast, there are no power plants newly constructed for BioCCS in NRW.

11 See the comparison of the so-called ‚Big Five' scenarios for climate neutrality in Germany: Prognos et al. 2021, BCG 2021, dena 2021, Fraunhofer ISI 2021, Kopernikus-Projekt Ariadne 2021) in (Kopernikus-Projekt Ariadne 2022)

Industrial sites for carbon dioxide removal as a synergy in 2045 are as follows:

- **Lime and cement:** In the lime and cement industry, biogenic energy sources based on residual materials are used to some extent for high-temperature process heat. This means that, in addition to the process-related CO_2, up to a third of the biogenic CO_2 can be captured as proportional negative emissions.

- **Waste incineration:** Due to the amounts of CO_2 produced here, waste incineration plants and sewage sludge incinerators (regardless of their intended use or supply purpose) are point sources that could be connected to a CO_2 transport infrastructure. This would prove useful for many locations in North Rhine-Westphalia. The biogenic portion of the captured CO_2 is available for CDR. Due to increasing circularity, waste avoidance and a growing share of biogenic plastic, the biogenic portion of waste has increased in some places. At the same time, growing competition for the biogenic fractions has led to rising prices and lower availability of residual and waste biomass, resulting in regional differences.

- **Glass production:** While many glass manufacturers have switched to hydrogen or fully electric or hybrid furnaces (green electricity/hydrogen), other sites suffering from a lack of hydrogen availability have replaced natural gas with biomethane. At the point sources with process-related CO_2 generation, these CO_2 amounts are captured together with the biogenic CO_2 amounts from biomethane combustion. Other sites, by contrast, have already been able to shift some of their process emissions upstream by changing the raw materials. In this way, the process-related CO_2 amounts are captured and stored or used directly by the raw material manufacturer. At sites where CO_2 emissions in waste gas are very low due to the switch to climate-neutral energy sources, adaptation of raw materials and a high proportion of recycling, residual emissions are offset by negative emissions. Whether biomethane and CO_2 capture will continue to be used in the glass industry well beyond 2045 is still an open question. This is partly product-specific (flat, special or container glass) and partly site-specific (regional availability of biomethane and hydrogen as well as a CO_2 transport connection). In this way, the glass industry is at least avoiding emissions and in some cases even generating negative emissions.

- **Energy sector:** Biomass (combined heat and) power plants that already exist in North Rhine-Westphalia before the development of a CO_2 infrastructure contribute to the biomass utilisation hierarchy by recovering energy from residual materials that can no longer be used as materials[12] and make the biogenic CO_2 available for use and for generating negative emissions. Due to the limited availability of sustainable biomass, hardly any new biomass (heat and) power plants have been built.

- **Biogas treatment and upgrading:** Biomethane from industrial and municipal sewage treatment plants as well as agriculture and waste management has played an important role in replacing fossil natural gas. When biogas is upgraded to biomethane, biogenic CO_2 is separated[13] and, where the plants are connected to a CO_2 transport infrastructure, made available as negative emissions or biogenic CO_2 for use. In plants where separation is worthwhile due to the quantities of CO_2, but where no CO_2 transport infrastructure is available, the CO_2 is liquefied and transported to CO_2 hubs. Limited quantities of renewable hydrogen are also produced from biomethane. Established processes such as steam reforming, in which hydrogen and CO_2 are produced and the CO_2 is captured separately, are already being used for this purpose. This biogenic CO_2 can be stored geologically and is counted as permanent carbon removal. Alternatively, the biomethane can be converted into hydrogen by methane pyrolysis, in which biogenic carbon black is formed, which is then introduced into products or soils and stored – with a certain degree of uncertainty regarding permanence.

- **Steam crackers:** In the first step, the energy supply of steam crackers was decarbonised by means of electrification or by switching to hydrogen. The hydrogen required can be produced by reforming or pyrolysis of the process methane produced in the steam cracker. Solid carbon produced during pyrolysis can be used as a carbon source in other

12 See also NRW.Energy4climate (2023).

13 This process is anything but new. CO_2 has always been captured during the processing of biogas into biomethane, but until now the CO_2 was released (as of 2024).

processes. CO_2 produced during reforming is captured and partly stored geologically. As the conversion from fossil to biogenic, CO_2-based (synthetic) or recycling-based feedstocks increases, more and more biogenic or atmospheric CO_2 will be captured. Some of this will be used as a carbon source for CCU. Some of this carbon, which is usually bound non-permanently in the products of the downstream industries, can in turn be captured in waste incineration plants and then reused or stored. Negative emissions are only generated if there is permanent storage, i.e. either with the CO_2 amounts directly captured during reforming, with permanent chemical bonding in products, or with the CO_2 quantities captured in downstream waste incineration (with the corresponding MRV challenge of tracking and accounting).[14]

- **Other industries with biogenic material flows:** For example, in the paper, alcohol and sugar industries, there is a significant amount of biogenic residues. Where possible, these are increasingly being used e.g. for biochemical products. At the end of the biomass cascade, however, there is still a certain potential for energy recovery with CO_2 capture on the basis of the long-established material flows and supply chains of these industries. In some of these cases, therefore, negative emissions are generated as a synergy to existing processes. However, this is only possible at sites that could be economically connected to a CO_2 infrastructure. In principle, the use of CCS is not necessary for decarbonisation in these sectors and the material use of biomass is preferable to its use as energy (see Chapter 3). It is therefore only certain suitable sites and processes, some of which are classified as transitional solutions, that are suitable for industrial carbon dioxide removal.

In addition to these BioCCS processes, plants for **Direct Air Capture (DAC)** have also been installed in North Rhine-Westphalia, although these are limited to a few demonstration plants or to the decentralised supply of CO_2 for CCU processes. Energy prices in NRW were not competitive enough in an international comparison in the key years for scaling the technology. Thus, large-scale DAC plants have been built in other regions with more suitable local conditions and plenty of space for renewable energy. Manufacturers from North Rhine-Westphalia have positioned themselves on the global market for this future market, creating significant value-added potential for the region. In its role as an exporter of key clean technologies, the state NRW benefits from the fact that Direct Air Capture plants consist partly of conventional components that have been manufactured here for a long time (IN4climate.RR 2022).

Operators of transport and storage infrastructure have included the additional amounts of biogenic and atmospheric CO_2 at an early stage in the design and capacity of transport and storage infrastructure and can thus make their necessary contribution in the supply chain to achieving negative emissions.

In addition to the CO_2 infrastructure, the expansion of the **energy infrastructure** has also been successful, so that the energy demand of the energy-intensive plants for point source CO_2 capture, direct air capture and the CCU processes[15] can be met from renewable sources.

Overall, the ramp-up of carbon dioxide removal in NRW has created further added value. CCS and CCU plants, as well as plants for the collection, processing and sorting of biogenic residues and waste materials, and for pyrolysis, are a field of activity for mechanical and plant engineering, each with export opportunities. (Herhold et al. 2024). Further value has been added in the service sector, for example in insurance, financial services, certification bodies, the qualification and further training sector, as well as in research and development, which continues to be necessary.

14 The transformation of the value chains in the chemical industry is complex. Therefore, a future scenario for the future integration of steam crackers from 2024 is subject to considerable uncertainty. The crucial point is that if the feedstock for the steam cracker is based on atmospheric C/CO_2, there is a theoretical potential for negative emissions. The extent to which this is actually implemented can vary greatly from plant to plant and is also a challenge in terms of permanence and accountability.

15 At least the same amount of energy that has so far been obtained by burning carbon-containing compounds to form CO_2 must be expended to produce the energy-containing compounds from the CO_2 again.

2.2 Conclusion: Synergies for industrial CDR

The above vision shows that Carbon Dioxide Removal can build on existing industrial processes. Synergies arise either where CO_2 has to be captured anyway, or where process-related biogenic residues accumulate and are used for energy generation. These synergies should play an important role in the ramp-up phase of Carbon Dioxide Removal in North Rhine-Westphalia – with relevant potential for achieving comparatively low prices per tonne of CO_2 captured.

BioCCS can therefore be implemented on a significant scale in industry, especially in sectors where CO_2 emissions are hard to abate. By contrast, power generation plants make significantly less sense, as there are sufficient low-cost renewable energy alternatives available for this purpose. Energy generation from biomass is therefore increasingly taking a back seat given the current pace of expansion of wind and solar power, while the value of negative emissions is becoming more and more important the closer NRW comes to its goal of greenhouse gas neutrality.

Furthermore, there is a noticeable difference compared to the previous debate on industrial carbon management: there are areas of application for permanent negative emissions using CCS even in sectors that are not confronted with „hard-to-abate" CO_2 formation. These are industries that already utilise biogenic residues, such as sewage treatment plants and biogas plants. In other sectors, the transformation pathways are still subject to uncertainties (or very site-specific) due to the still uncertain local availability of large amounts of electricity and hydrogen. Particularly in the provision of high-temperature process heat, such as in the glass industry, or the internal energy use of biogenic residues, such as in steam crackers, the potential for the synergetic generation of negative emissions therefore depends on the site-specific availability of biomass compared to hydrogen and electricity. At sites that can be connected to a CO_2 infrastructure, a business model for the capture and storage of biogenic CO_2 can emerge in the future through permanent CDR certificates. It therefore makes sense that these industries are not excluded by the Carbon Management Strategy and the Carbon Dioxide Storage and Transport Act from using CCU/CCS technologies and the CO_2 infrastructure.

3 Trade-offs and limitations of CDR

With the expansion of industrial Carbon Dioxide Removal, several trade-offs are to be expected that are likely to have a limiting effect on the scaling of the respective applications. In order to minimise negative side effects, it is important to keep them in view on an ongoing basis. At the same time, they show the necessity of implementing the carbon management hierarchy in the overall system with a view to interactions.

3.1 Limited availability of sustainable biomass: a utilisation and land-use trade-off

The extent to which negative emissions arise from BioCCS on a life-cycle basis depends heavily on the sustainability of the biomass used. There is limited availability of sustainable biomass and arable land. At the same time, the area of land available for natural sinks should increase in order to remove CO_2 from the atmosphere naturally and achieve biodiversity targets. In view of this competition for land, it is important to use the limited sustainable biomass as efficiently as possible. Before biomass can be used as an energy source, its other potential uses must be exhausted in line with the cascading principle – at the structural and material level (NRW.Energy4Climate 2023).

For example: a building material or piece of furniture is first made from the raw material wood, and the resulting sawdust is used to make chipboard (structural use). Wood residues, including old chipboard, can in turn serve as a carbon source for material use, for example in the chemical industry. Residual materials such as straw and leftovers from the food or pulp industry can also be used materially. By replacing fossil raw materials, this plays an important role in many areas on the road to greenhouse gas neutrality (first priority: reducing CO_2 formation) and leads to efficient multiple use before it is sent to an incinerator.

In a strict use hierarchy, only residual and waste materials are earmarked for energy recovery and the subsequent capture of CO_2 for negative emissions using BioCCS. The production of biochar is another non-permanent CDR process that requires biogenic residues and could constitute a conflicting use, which needs to be taken into account when ramping up CDR methods. This focus on residues at the end of the biomass cascade for BioCCS ensures that the sustainable potential of limited biomass resources is utilised in a sensible way.

3.2 Volatile availability of renewable energy

As long as renewable energies are not yet continuously available to a sufficient extent to cover the entire energy requirements for NRW at all times, they should be used where they contribute most efficiently to avoiding CO_2 formation. This is primarily the case when industrial processes are directly electrified.)[16]. CCS/CCU technologies consume a lot of energy to scrub the CO_2 from the point source flue gas. The overall balance is only achieved if this large energy demand can be met by renewable energies. It therefore makes sense to prioritise CCS in the first instance for „hard-to-abate" applications[17] and to operate CCU in particular on the basis of energy from overproduction at peak times. The most important means of keeping this trade-off manageable in any case remains the rapid expansion of renewable energies and storage capacities in order to overcome the scarcity and volatility of renewable energies, particularly in NRW.

16 This also includes the demand for renewable energies (RE) for the production of renewable hydrogen – with a certain special role, since hydrogen is also needed for defossilised hydrocarbons and thus, as CCU processes scale up, the demand for renewable hydrogen will continue to increase. Depending on how much renewable hydrogen is imported, the trade-off with other RE demands will be more or less pronounced.

17 See Carbon Management Strategy NRW and also E3G & Bellona (2023).

Due to the low concentration of CO_2 in the atmosphere (approx. 420 ppm CO_2), the direct separation of CO_2 from the atmosphere using direct air capture technologies requires a significantly higher energy input than the separation at point sources. This means that as long as renewable energies are still scarce at times, the separation of CO_2 at point sources should be prioritised, as this is both energetically and economically more favourable and thus offers greater potential for reducing emissions.

3.3 Limited availability of non-fossil carbon as a raw material

In parallel to the expansion of renewable energies, the production and use of alternative, non-fossil carbon sources (defossilisation) must be initiated in order to achieve greenhouse gas neutrality. In view of the above-described trade-offs, it is expected that atmospheric[18] CO_2 amounts in NRW will not be sufficient to provide the required quantities of carbon (e.g. for the production of chemical base materials) for the period up to 2045. The goal of defossilising the chemical industry and the goal of negative emissions can therefore compete in terms of the amounts of CO_2 required. In the long term, CDR, CCS and CCU are important building blocks for avoiding a further increase in greenhouse gases in the atmosphere. During the ramp-up phase up to 2045, it is important to ensure that the portfolio of these building blocks is scaled in a differentiated manner in terms of time and technology in order to avoid trade-offs and negative side effects.

18 This implies both BioCCU/S and DACCU/S (see above).

4 Need for action

The framework for accounting for industrial negative emissions and trading them as certificates with a market value is still lacking. In the long term, it is unlikely that the voluntary carbon market will suffice as a market mechanism. The German government‘s Long-Term Strategy on Negative Emissions (LNe) identifies the most important issues that need to be clarified, such as creditability, economic incentives, a legal framework and MRV (monitoring, reporting and verification), as well as social acceptance.

However, since the applications described here are at the core of the industrial transformation, and investment decisions for the following decades are now being made, it is clear that a prospect is needed by 2025. The first CCS plants for waste incineration and for the cement and lime industry are currently being dimensioned and planned. These systems must be designed now so that they can capture biogenic CO_2 for Carbon Dioxide Removal in addition to the process-related fossil CO_2 amounts. This means that clear incentives, legal and investment security are needed more quickly than for other CDR applications. The window of opportunity that opens up following the publication of the Carbon Management Strategy and the passing of the Carbon Dioxide Storage and Transport Act should be used to this end, so that the infrastructure and facilities that will inevitably be built will already enable the synergies for carbon dioxide removal.

High quality and reliability of the CDR certification is part of the conditions for investment security. The extensive investments can only be justified if there is a secure and demonstrable value for negative emissions. A suitably high certificate price can be justified by a high level of reliability of the system and the associated high level of trust in the certification. To achieve this, it is necessary to keep technically generated, permanent negative emissions clearly distinguishable from non-permanent sinks and to provide different incentives for each. This is how the limited comparability can be taken into account.

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EUREF-Campus 1c
40472 Düsseldorf

kontakt@energy4climate.nrw
www.energy4climate.nrw

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