CO_2 IN A CLIMATE-NEUTRAL BASIC MATERIALS INDUSTRY: INFRASTRUCTURE REQUIREMENTS FOR NRW

Discussion paper of the working group on the carbon dioxide economy

The content of this document is supported by the following partners:

Air Liquide, BFI, Covestro, Fraunhofer UMSICHT, HeidelbergCement, IW, Kalk, LANXESS, Lhoist, RHM Die Rohstoffhändler, LTT RWTH Aachen University, SCI4climate.NRW, Solvay, Spenner, thyssenkrupp, vdz, Wirtschaftsvereinigung Stahl, Wuppertal Institut

IN4climate.NRW is an initiative of the state government of North Rhine-Westphalia:

Ministry of Economic Affairs, Innovation, Digitalization and Energy of the State of North Rhine-Westphalia

IN4climate.NRW draws its strength from discussion and the various points of view put forward by its participating companies and organisations. IN4climate.NRW does not see itself as an association that actively promotes the interests of its members at political level. Instead, the initiative provides a platform for dialogue and the exchange of ideas. This environment gives rise to papers and studies that are developed, discussed and elaborated on by individual members. As part of a structured process, other members have the opportunity to explicitly support the findings or discussion contributions and endorse the document in question. All the IN4climate.NRW members who choose to endorse the resulting findings are clearly listed in the interest of transparency. However, this should not be viewed as an indication of the position taken by other IN4climate.NRW members who have not been listed. IN4climate.NRW's Head Office seeks to ensure transparency and opportunities for participation.

Authors:	Dr Christoph Glasner (Fraunhofer UMSICHT), Dr Iris Rieth (IN4climate.NRW), Dr Johannes Ruppert (VDZ), Prof Ulrich Seifert (Fraunhofer UMSICHT), Christoph Zeiss (Wuppertal Institut)
Contributors:	Frank Balzer (Air Liquide), Andreas Fischer (IW), Dr Lukas John (IN4climate.NRW), Prof Stefan Lechtenböhmer (Wuppertal Institut), Dr Frank Ohnemüller (FG Kalk und Mörtel), Theresa Overbeck (BFI), Dario Zander (Wuppertal Institut), Christian Zibunas (LTT RWTH Aachen)

Bibliographic information

Publisher:	IN4climate.NRW
Date of publication:	October 2021
Coordination:	Dr Iris Rieth (IN4climate.NRW), Dr Christoph Glasner (Fraunhofer UMSICHT), Christoph Zeiss (Wuppertal Institut)
Contact:	iris.rieth@energy4climate.nrw
Please reference as:	IN4climate.NRW (Ed.) 2021: CO_2 in a climate-neutral basic materials industry: Infrastructure requirements for NRW. Discussion paper by IN4climate.NRW. Gelsenkirchen.

OUR KEY MESSAGES

Process-related CO_2 will necessarily still be produced due to certain industrial processes even if North Rhine-Westphalia (NRW) is climate-neutral in the future. This CO_2 will need to be captured and collected so that it is not emitted into the atmosphere. Captured CO_2 can be geologically stored for long periods (CCS) or used as a source of carbon for new products (CCU). In the view of IN4climate.NRW's working group on the carbon dioxide economy, future CO_2 produced in NRW will either be sent to CO_2 storage sites or used in industry. Both options require capture technology and CO_2 infrastructure to be developed. On the one hand **technical questions** still need to be resolved by **industry** and the **scientific community**. For example, what level of CO_2 purity is required for each option and what capture and cleaning facilities are needed? **Politics**, on the other hand, needs to create the **legal framework** and **instruments** to make a carbon dioxide economy possible. This includes:

- Ratifying the Amendment to Article 6 of the **London Protocol** and implementing it into national law by means of Federal legislation to allow CO_2 to be stored in international storage sites,
- Drafting bilateral agreements that are conditional on Article 6 of the London Protocol for transporting CO_2 across borders,
- Adjusting Germany's legal framework on transporting CO_2 for the purposes of using and storing carbon dioxide,
- Creating regulations that define credits for uses of CO_2 (and negative emissions, if applicable) in the **EU-ETS**.

On top of this, however, a few key inhibitors can only be solved **jointly** by industry, politics and the scientific community:

- Developing a **communication strategy** for social discourse on the carbon dioxide economy in Germany,
- Defining "permanently chemically bound" CO_2 so that **credits in the EU-ETS** are clearly regulated,
- Developing a **step-by-step plan** for CO_2 infrastructure and taking this into account in both the **network development plan** and the **TEN-E regulation**,
- Providing start-up support for a carbon dioxide economy in **real-world laboratories** in NRW.

LIST OF ABBREVIATIONS

BECCS	Bioenergy with Carbon Capture and Storage
BImSchG	German Federal Immission Control Act (BImSchG)
BImSchV	German Federal Immission Protection Ordinance (BImSchV)
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAC	Direct Air Capture
EU-ETS	EU Emissions Trading System
GHG	Greenhouse Gas
NRW	North Rhine-Westphalia
OPEX	Operational Expenditure
PtX	Power-to-X
TEN-E	Trans-European Networks for Energy
VDZ	German Cement Works Association
WTE	Waste-to-Energy

CONTENT

1. INTRODUCTION

Climate change and the climate targets it has inspired pose a tremendous challenge for the basic materials industry in North Rhine-Westphalia. Carbon-neutral industry in North Rhine-Westphalia that maintains the creation of value is certainly possible. However, it requires appropriate infrastructure and a reliable political framework. Developing infrastructure is always a long-term process that must be started and implemented based on the most accurate and reliable predictions possible. In terms of transport, previous plans have only considered infrastructure for the supply of electricity, natural gas and hydrogen (electricity and gas network development plans). Carbon dioxide has not been included in any previous infrastructure plans in Germany despite the urgent need for strategies that will prevent carbon dioxide from being emitted and instead ensure that it is captured or bound – if production of CO_2 cannot be avoided.

The need and requirements of appropriate infrastructure for transporting CO_2 were the subject of opening discussions in a joint workshop hosted by the German Cement Works Association (VDZ) and the state government initiative IN4climate.NRW, including its scientific competence centre, SCI4climate.NRW. Industry, NGOs and the scientific community were all involved in the discussions (VDZ 2019), which were followed by a comprehensive examination of unanswered questions in IN4climate.NRW's working group on the carbon dioxide economy and in the drafting of climate protection scenarios for industry by SCI4climate.NRW. Unavoidable CO_2 production in NRW (IN4climate.NRW 2020) and the basic legal issues of a carbon dioxide economy were investigated (Benrath 2021).

IN4climate.NRW's working group on the carbon dioxide economy discussed possible options for managing volumes of process-related CO_2 and documented these ideas in this paper. It discusses CO_2 volumes in a carbon-neutral basic materials industry in NRW, possible options for managing these volumes and what necessary infrastructure developments can be expected. The working group on the carbon dioxide economy also provides recommended actions to best implement and streamline said infrastructure developments.

2. REMAINING VOLUMES OF CO_2 IN A CARBON-NEUTRAL INDUSTRY IN NRW

Process-related emissions from the basic materials industry present a considerable challenge for carbon neutrality, as CO_2 production presumably cannot be avoided in certain manufacturing processes – assuming that the basic materials in question are still produced in the future. However, some CO_2 emissions derived from fuels are also unavoidable from a current perspective, as many processes (e.g., manufacturing cement clinker) will likely also require carbon-based fuels in the future and it is unclear whether hydrogen can cover all the needs for fuel energy. The Wuppertal Institute published a study (SCI4climate.NRW 2021a) in cooperation with the VDZ, the VDEh-Betriebsforschungsinstitut (BFI) and other scientific partners that presented three scenarios for a carbon-neutral industry in NRW. The study aimed to identify ranges for volumes of CO_2 produced in the basic materials industry. Industrial processes with (practically) unavoidable CO_2 production over the long term formed the basis of the study. Future CO_2 production at industrial point sources in a carbon-neutral NRW was estimated in three separate scenarios that each consider the industrial sector's integration into the energy system in different ways. Each scenario represents the hypothetical vision of a climate-neutral industry. Estimates for production volumes in 2045 as compared to today (base year 2016) are the same in each scenario. They are based on historical trends, published scenario studies on the development of specific sectors, in-house expertise and considerations to ensure consistency. (ibid.) The three scenarios do not yet consider possible sufficiency or efficiency in production volumes.

- **Tech_Min scenario:** this scenario assumes the minimum level of CO_2 production that is theoretically possible (from a technical standpoint) for each facility as a point source. It assumes that the extremely high demand for renewable energy, which would arise from the transition of certain processes, can be covered and that the required infrastructure will be available at each location.

- **SYS scenario:** this scenario looks beyond the industrial sector and takes the whole system into account. It presents a trade-off between the following factors (and is plausible in the view of the Wuppertal Institute):
  - Minimising CO_2 production from industrial sources,
  - Resulting demand for renewable energy,
  - Infrastructure needs,
  - Costs,
  - Other systemic effects (e.g., shift of waste flows).

  In comparison with the Tech_Min scenario, CO_2 in SYS comes primarily from waste-based alternative fuels used to produce cement clinker and quicklime as well as thermal use of feedstocks in steam crackers.

- **BECCS scenario:** this scenario is broadly the same as the SYS scenario and is based on the study titled "Klimaneutrales Deutschland" (Climate-neutral Germany) (Prognos et al. 2020). However, huge amounts of biogenic energy sources (gasified biomass) are used (in combination with CCS) to generate negative emissions (BECCS) to supply process steam to the basic chemicals industry and high-temperature heat to the mills in the steel industry.

Analysis of the SYS scenario by the Wuppertal Institute identified 50 locations that form part of the basic materials industry (iron and steel, basic chemicals, cement, lime and glass) in North Rhine-Westphalia.

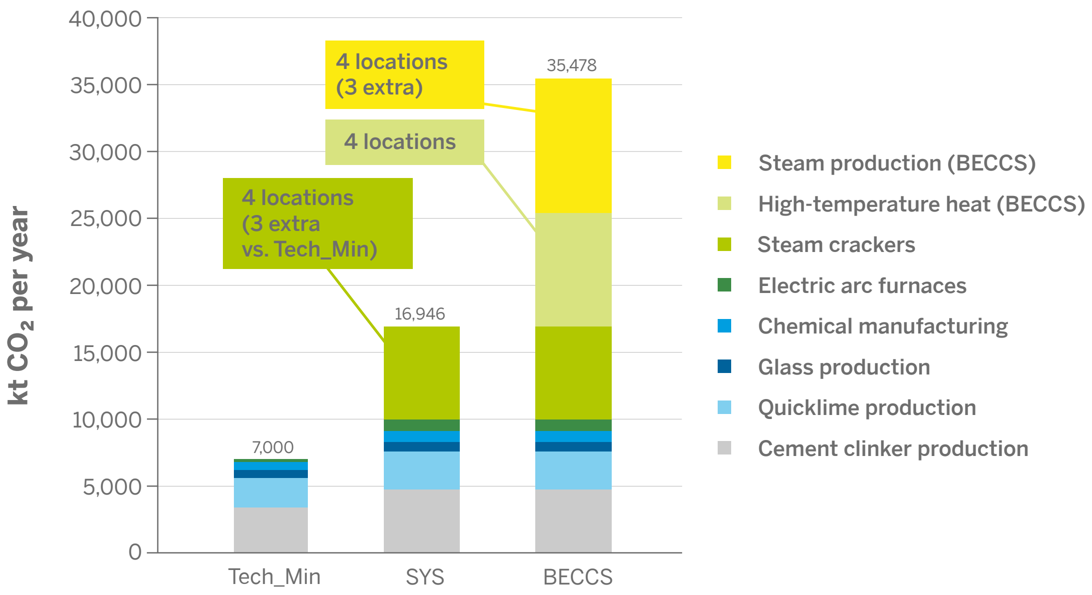


Illustration 1: CO_2 production from industrial sources in NRW in a carbon-neutral industry in 2045 (SCI4climate.NRW 2021a)

The study shows that carbon-neutral industry in North Rhine-Westphalia would continue to produce CO_2 in each of the three scenarios, albeit with wildly different volumes. Furthermore, CO_2 production occurs at many different locations in the three scenarios (see Illustration 1). The goal of the Tech_Min scenario is to estimate the theoretical minimum future production of CO_2; achieving this minimum however would require huge amounts of renewable energy, which could be used more effectively and profitably elsewhere when taking the entire energy system into consideration. Nevertheless, CO_2 will still be produced in all three scenarios. As such, solutions will have to be found in the course of industry transition to handle these CO_2 amounts and ultimately achieve a fully carbon-neutral system.

3. MANAGING CO_2 VOLUMES THAT ARE STILL PRODUCED

3.1 Capture

Process-related CO_2 production from input materials occurs in several industrial processes that are considered vital in the manufacture of basic materials. If CO_2 production proves unavoidable in the process itself, the emission of the CO_2 into the atmosphere must be prevented in order not to jeopardise the climate targets. In these cases, it will be necessary to capture the CO_2 produced by the process. Past and current European research and pilot projects are investigating methods for capturing CO_2 from industrial processes in terms of their suitability, requirements and technical implementation.

CO_2 capture in its strictest technical sense refers to any processing steps that ensure the carbon dioxide contained in a (process) gas mix is sufficiently pure and in a compressed, gaseous, condensed or liquefied state for removal or further use. CO_2 capture in a broader sense also refers to any changes to the main upstream processes that aim to significantly increase the concentration of carbon dioxide found in the waste gas of these processes. The higher the concentration of carbon dioxide already present in the starting mix, the lower the minimum amount of energy required to convert it into a nearly pure form. In addition to the capture of carbon dioxide at the end of a main process (e.g., post-combustion capture), there are also processes that separate carbon – in the form of carbon dioxide – before the main process and feed it out of the process altogether.

While CO_2 capture in petrochemical processes, and in relation to generating syngas, has been state of the art for some time, other technologies are now ready for industrial CO_2 capture in other environments or demonstration at an industrial scale (ECRA 2020). The latest developments in CO_2 capture can be found in the reports of countless research projects over the last few years (see **info boxes**) and also in Technical Reports 27912 and 27922 from ISO (ISO/TR 27912:2016(en); ISO/TR 27922:2021(en)).

State of the art in CO_2 capture in the lime and cement industry

The cement industry's focus regarding the capture of process-related CO_2 production currently rests on oxyfuel combustion and post-combustion technologies (Hoenig et al. 2012, IEAGHG 2013, ECRA CSI 2019), although other methods are also being tested. Plans are ongoing for the creation of a demonstration plant working on the pure oxyfuel principle (Thomas 2019), while amine scrubbing is already being tested in the cement industry at both pilot and demonstration-scale (Brevik 2017; CemNet 2019a). The calcium looping process is particularly suited to the lime and cement industry because quicklime (CaO) serves as an adsorbent. Different variations are currently being tested in pilot projects (LEAP o. J.; TCC 2017). The lime industry is also working on a process for CO_2 capture using a solid-bed reactor as part of the AiF-IGF Project 21261 BG (2020-2022) (AiF 2020). Plans are already being made to scale the project up at a lime plant and create a real-world laboratory (BVK o. J.). A pilot plant for indirect calcination, in which CO_2 from raw materials is produced separately from CO_2 from fuels, has been operating at a Belgian cement plant for several years (LEILAC Project o. J.) – a larger facility is currently being planned (CemNet 2019a).

State of the art in CO_2 capture in the steel industry

Different technologies for CO_2 capture are undergoing intense research in the steel industry. The process gases of integrated blast furnace routes, steel mill gas-to-energy power plants and waste gases from direct reduction powered by natural gas are the focus. The ULCOS project investigated CO_2 capture and feeding CO-rich waste gases back into blast furnaces (top gas recycling), which increases the concentration of CO_2 in the gas and therefore also improves the efficiency of CO_2 capture (Leeson et al. 2017). The Stepwise project is currently investigating pre-combustion technology using the water-gas shift reaction to form CO_2 from CO. The hydrogen produced is used as fuel (The Stepwise SEWGS Project o. J.).

CO_2 produced at direct reduction plants powered by natural gas can be captured using amine-based absorption (Tenova HYL et al. 2020). Moreover, research is also currently being conducted into membrane processes for use at direct reduction plants. Projects such as Carbon2Chem® are demonstrating the capture and use of CO_2 for basic materials in the chemical industry (Deerberg et al. 2018).

In addition to the future CO_2 point sources considered in this paper, diffuse CO_2 emissions will also be produced (e.g., from farming and aviation). If these cannot be avoided, they will have to be offset to achieve climate neutrality. Aside from reforestation and BECCS, Direct Air Capture (DAC) technology presents a possible technical solution. However, it is very energy-intensive to achieve sufficient concentrations of CO_2 from the atmosphere using DAC. As such, the priority should be to avoid the production of CO_2 whenever possible and use more energy-efficient capture at point sources with high CO_2 concentrations (using the methods described above).

3.2 Use

Carbon dioxide is currently used in a multitude of different processes and applications, thanks largely to its specific material properties. This includes physical applications (e.g., as coolant in the form of dry ice, as refrigerant in closed refrigeration circuits, as blasting material, extinguishing gas or inerting gas) as well as use in the food industry. Moreover, carbon dioxide is a raw material for chemical and biochemical reactions. In this context, natural photosynthesis, which helps biomass form and develop through the combination of carbon dioxide, water and energy in the form of light, plays a special role.

Given the aim of industry reaching climate neutrality, technical uses for carbon dioxide that lengthen the carbon cycle (from supply to release of CO_2 emissions in the atmosphere) are of particular interest. In the ideal scenario, they will also contribute to closing the carbon cycle in the long term. technical uses of CO_2 help minimise the amount of carbon released into the technosphere and biosphere from energy-rich fossil fuels (coal, crude oil and natural gas). It is in principle feasible to supply the necessary raw materials for the majority of organic and chemical products that industry requires via the intermediate step of methanol synthesis from CO_2 and hydrogen (Kätelhön et al. 2019).

A key challenge regarding the use of CO_2 as a carbon support material for chemical reactions is increasing the low energy content of carbon dioxide. To create more energy-rich end products, more energy-rich reaction partners have to be used, in particular hydrogen, or energy has to be added in some other way (e.g., electrochemically).

CO_2 as a raw material for urea synthesis

Industrial processes have already been set up to use CO_2 as a raw material and bind it in products. Of these processes, urea synthesis from ammonia and carbon dioxide is the most important in terms of global production volume (Otto et al. 2017). In the case of ammonia produced from natural gas, the carbon dioxide required for urea synthesis is already available as surplus from pre-processing. It can therefore be used on-site, which of course helps reduce CO_2 emissions. Urea production may provide additional potential for CO_2 binding when ammonia can be produced without using carbon fossil fuels, for example, using green hydrogen from renewable energy sources instead.

If carbon dioxide is to be used chemically to help reduce emissions, it is vital – in order to produce energy-rich products – that the necessary energy is provided by energy-rich reaction partners with a low GHG footprint (acatech (Hrsg.) 2018). This is the only way to ensure a positive overall impact (ibid.). At the same time, climate-neutral production of carbon-based Power-to-X products (e.g., from methanol or naphtha) at locations with inexpensive and readily available renewable energy will require carbon to be supplied in the form of carbon dioxide. This could be supplied locally using DAC, by burning biomass with subsequent CO_2 capture or by delivery from sources with more energy-efficient CO_2 capture. With a view to CCU, this means that future carbon capture (CC) and use (U) of carbon dioxide need not necessarily occur at the same location.

A different situation arises in terms of energy when carbon dioxide is bound in basic materials such as concrete (mineralisation/recarbonation). The equilibrium of these processes under ambient conditions normally lies strongly in favour of the respective carbonates. This means that – unlike the CO_2-based synthesis of energy-rich products – this chemical reaction pathway does not require any additional energy input. In the life cycle of lime-based products, recarbonation occurs naturally in a variety of applications, creating permanent mineral bonds of CO_2. Technical means can be used in several applications to increase the natural re-uptake of CO_2 (EuLa 2021), for example, in the iron and steel slags of blast furnaces and converters (DECHEMA o. J.) or when recycling cement (VDZ 2020). CO_2 can partially be used and mineral-bonded at much earlier stages, for example, during the production of lime and concrete products (Grosso et. al 2020, Ruppert et al. 2019). Additional mineralisation/recarbonation can involve different levels of complexity regarding logistics and the processing of suitable materials. Aside from using CO_2, the final permanent mineral binding of CO_2 is certainly advantageous.

The carbon cycle must be closed to achieve climate neutrality. CCU is one possible option to help achieve this and also avoids GHG emissions that accompany the supply of carbon from fossil resources biomass by repeatedly reusing the carbon. The possibilities and potential of CCU will be assessed separately at a later date.

3.3 Storage options

While CCU aims to reuse carbon dioxide, or rather the carbon that it contains, the aim of Carbon Capture and Storage (CCS) is to remove carbon dioxide from the cycle and store it for long periods.

Storage options in Germany

Geological storage of CO_2 in Germany is currently precluded by law (Benrath 2021). Following the largely prohibitive carbon dioxide storage law enacted in 2012, neither the infrastructure and storage sites, nor the required political and underlying societal conditions have progressed any further. Germany's geological storage capacity for CO_2 has been calculated at between 6.3 and 12.3 gigatons of CO_2 (Gt CO_2) (Knopf et al. 2010). A research and pilot project into the geological storage of CO_2 was successfully completed at the Ketzin site in Brandenburg (GFZ 2004). However, whether future storage in Germany will be possible is a moot question. The working group on the carbon dioxide economy is therefore focussing on storage options outside of Germany.

Storage options outside Germany

International project consortia have formed to develop long-term, geological storage options and ultimately be able to offer this as a service. "Strategy CCUS" is one such project within the EU, which is looking into storage options in southern and eastern Europe – both onshore and offshore (Rocha 2021). 8.5 gigatons of CO_2 has been touted as the potential capacity of storage sites in southern and eastern Europe (ibid.). The geological surface layers under the North Sea are considered to offer the largest storage potential, where CO_2 can be permanently stored in saline aquifers, sandstone or in depleted geological storage sites for crude oil and natural gas. Possible capacity off the coast of Norway and the UK is currently estimated at between 61 and 73 gigatons of CO_2 (ECRA 2020; Global CCS Institute 2020). However, large areas still need to be explored.

For Germany, and NRW in particularly, underground offshore storage of CO_2 below the North Sea stands out on account of its proximity and various possible routes of access. Various companies with projects in the North Sea are courting attention as possible future service providers of CO_2 storage. Illustration 2 outlines three such projects. Further projects can be found in on the European Zero Emissions Platform (ZEP 2021), for example, and are located in Iceland and Denmark among other countries.

Acorn, Great Britain

- 2 Mt CO_2 / year from 2023 onwards
- Capacity: 150 Mt CO_2

Porthos, the Netherlands

- from 2024 onwards
- Target: 2.5 Mt CO_2 / year
- Capacity: 37 Mt CO_2

Northern Lights, Norway

- 1.5 Mt CO_2 / year from mid-2024 onwards
- Target: 5 Mt CO_2 / year
- Capacity: 100 Mt CO_2

Illustration 2: Examples of CCS projects in Europe (Porthos and ACT Acorn Consortium 2019, Smit 2021, Northern Lights and Arends 2021), figures in megatons of CO_2 (Mt CO_2)

3.4 Transport

CO_2 can be transported in different ways, including by pipeline, ship, rail and HGV. While transporting CO_2 via pipeline can be carried out continuously, transporting it via HGV, rail or ship involves discontinuous processes, which require interim storage of CO_2 before loading (at the location where the CO_2 is produced) and after unloading. Another difference lies in the legal classification of CO_2, which to date depends on both the mode of transport and the purpose of transporting CO_2 (use or storage). A report commissioned by IN4climate.NRW (Benrath 2021) provides an in-depth look at the current legal situation in Germany and uncovers various loopholes and shortcomings (see Section 5).

Transport via rail or HGV appears sufficient during the initial phase with small carbon capture projects. Transport via ship is also possible if the source of CO_2 is on or close to a waterway. An ISO container for transport by road can hold 20 tonnes of CO_2 (Ruban 2021). A rail tank wagon can hold up to 60 tonnes of CO_2 (ibid.), which means that a whole train can transport up to 1,200 tonnes of CO_2. Depending on the size of the ship, between 1,000 and 8,000 tonnes of CO_2 per load can be transported at 15 bar of pressure (ibid.). Pipeline infrastructure is therefore sensible when transporting larger amounts of CO_2 – which can be expected in NRW over the long term – irrespective of whether the CO_2 will be stored or used at a different location.

The ELEGANCY research project compared the economic feasibility of different transport options for CO_2 from sources in Germany to Porthos' storage fields – a total journey of around 5,280 kilometers: transport via ship (including loading and unloading) navigating rivers and canals to reach the storage sites in the North Sea would cost at least twice as much (at approx. 13.5 euro per tonne of CO_2) as constructing and operating pipeline infrastructure that would connect the CO_2 sources in Germany to the Porthos' storage sites (Benrath et al. 2020).

From a technical standpoint, CO_2 fed into pipelines must be of known composition to be able to guarantee the correct conditions for transport. Minimum requirements therefore need to be established – and complied with – for liquid transport of CO_2 (Brown 2021). Requirements concerning the quality of carbon dioxide transported in pipelines are addressed in detail in Technical Reports 27913 and 27921 (ISO/TR 27921:2020(en); ISO/TR 27913:2016(en)).

4. POSSIBLE INFRASTRUCTURE FOR TRANSPORTING CO_2 IN NRW

4.1 NRW infrastructure map

The Wuppertal Institute presented a possible vision for CO_2 infrastructure in NRW in a study (SCI4climate.NRW 2021a) as part of the SYS scenario for a carbon-neutral industry (see Section 2). This scenario assumes production of approx. 16.9 megatons of CO_2 per year. The design of this pipeline infrastructure was guided by CO_2 volumes, the geographic location of the point sources and the planned storage sites in the North Sea. As a basic principle, the design attempts to connect as many point sources as possible in a single infrastructure. In a few instances, some point sources were not considered for the following reasons: unfavourable geographic location (distance or impassable terrain) in relation to the remaining sources, lower CO_2 production or alternative means of transportation available (train).

The clustering suggested here incorporates 97 per cent of the CO_2 produced in NRW from the SYS scenario and connects 30 of the 50 locations in NRW by pipeline.

The 20 smaller point sources in NRW, which have not been taken into account in these initial projections, are often peripheral and located along the borders of NRW (northern, southern and eastern Westphalia as well as in the Aachen region). With an eye to the future, it would be possible to integrate these 20 locations into a pipeline system at a later date if individual cost-benefit analyses demonstrate this would be worthwhile. Local carbon sinks (for example, with CCU) have not been considered in this illustration and will require additional consideration in any planning phase (see Section 4.2).

The main findings (ibid.) are:

- For the volumes of CO_2 being produced and in consideration of the geographic location and infrastructure links between the locations, transporting CO_2 by pipeline is the most logical solution for a large majority of the locations.

- The cement and lime industries contribute a significant percentage of total CO_2 production in all scenarios considered.

- Future CO_2 emissions from steam crackers can have a significant impact on the total volume of CO_2 produced. Furthermore, the amounts of CO_2 resulting from steam crackers are produced in high concentrations at only a few locations. How CO_2 production at steam crackers will develop and change in the future is also fraught with uncertainties – including possible electrification, but also altered feed-stocks and possible competition from other methods of producing olefins and aromatic compounds. Special attention should therefore be paid to the future of steam crackers when planning CO_2 infrastructure.

- A specific BECCS strategy for generating negative emissions at steel and chemical industry locations would have little to no impact on the length and structure of a CO_2 pipeline system as the additional locations are situated close to the pipeline conceived in the SYS scenario. However, this must be kept in mind from the very start when determining and designing pipeline capacity on account of larger possible volumes of CO_2.

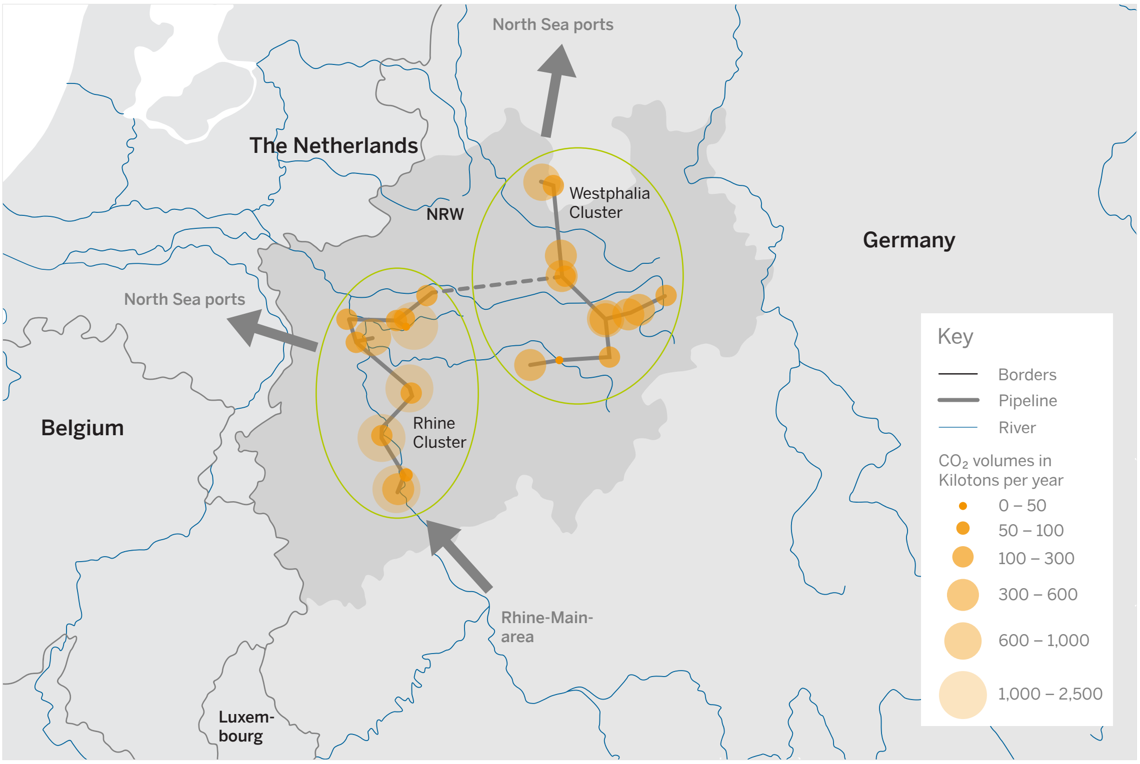


Illustration 3: Concept for CO_2 pipeline infrastructure for the Rhine and Westphalia cluster in the SYS scenario for climate-neutral industry, including possible connections and cross-connections (dashed) (as per SCI4climate.NRW 2021a)

Nevertheless, the CO_2 pipeline infrastructure concept for NRW presented as part of a study by the Wuppertal Institute (ibid.) only shows one possible configuration. Other infrastructure designs are conceivable ((ibid.); discussion in the working group on the carbon dioxide economy) and reveal a range of possible developments:

1. Alternative infrastructure option: focus on a CO_2 hub

The CO_2 infrastructure in NRW could instead simply focus on one CO_2 hub or destination port (Rotterdam or Wilhelmshaven). An approx. 100-kilometer stretch of pipeline could therefore be added to the infrastructure concept shown in Illustration 3 between the cement works in Beckum and the chemical park Marl.

2. Alternative infrastructure option: connecting the Rhine and Westphalia clusters

Connecting the Rhine and Westphalia clusters, from the chemical park Marl to the cement works in Beckum, would provide greater flexibility in transporting CO_2 as it could be transported to either Rotterdam or Wilhelmshaven. However, the dimensions of the connecting pipeline (and downstream connections) would have to be adjusted.

3. Alternative infrastructure option: connecting the Rhine-Main region

Possible volumes of CO_2 from bordering regions, which would flow through North Rhine-Westphalia, have not been included in the infrastructure concept shown. Adding a connection for transporting CO_2 from the Rhine-Main region, which could use the Rhine cluster connection at the chemical park in Wesseling, would appear a sensible option and could have an impact on the infrastructure in NRW.

4.2 CO_2 as a source of carbon

This paper has so far solely looked at infrastructure against the backdrop of how and where CO_2 can be transported or how negative emissions can be produced using biomass combined with CCS. This scenario is undoubtedly a useful starting point to help draft possible CCS infrastructure. However, the future is likely to present a more complex reality and require the infrastructures identified to be placed into a much larger context. This includes the fact that the chemical and petrochemical industries in particular will need enormous amounts of carbon to continue operating at their locations in NRW. The key question is therefore how to cover this demand. There are various options available to supply carbon, however, each requires very different CO_2 infrastructure. The most obvious options for the (petro)chemical industry are summarised below:

Option 1: carbon needs covered by biomass:

The amounts of available, sustainable biomass are already limited. There are no expectations for more biomass to be available in the future, particularly given the announcement from the German Federal Environment Ministry (BMU) in May 2021 (BMU 2021) that it will provide increased space for carbon sequestration, e.g., bogs. Moreover, the entire system needs to be optimised for the long term. Biomass is a potential source of carbon for steel production, a possible fuel for process heating and a raw material for chemical processes. But biogenic carbon will not be able to fully cover every conceivable application. The most efficient use of biomass (in the basic materials industry) therefore requires determination. For example, future use of biomass could be linked with production routes where unavoidable CO_2 production needs to be captured, as this would create the opportunity for negative emissions.

This means that it would likely not leave any sustainably produced biomass for the chemical industry, apart from recycling biogenic waste materials or CO_2 from exhaust gases given off by thermal use of biomass. Further investigation is required to determine the most beneficial use of biomass in competition with other sectors.

Option 2: carbon needs covered by CO_2 captured in NRW

Looking at the infrastructure maps in the SCI4climate.NRW scenarios investigated (SCI4climate.NRW 2021a), it is clear that the locations at which future CO_2 will still be produced will be relatively close to the locations of the chemical industry. To lock carbon into a cycle using CCU, the proposed Rhine cluster could look very different – namely much more like an interconnected CO_2 transport network. It is also conceivable that the Westphalia cluster could supply the locations in the Rhine cluster with additional carbon to cover demand when needed.

Option 3: captured CO_2 exported and carbon imported in the form of Power-to-X products (PtX) such as green naphtha

The price for emitted CO_2 is likely to increase significantly, especially over the long term, as this is an important mechanism for introducing new technology and converting processes that would not otherwise be economically feasible. At the same time, however, carbon will still be needed. Particularly in NRW, there is a comparatively higher concentration of industrial point sources of CO_2. This opens the option of exporting captured CO_2 as a raw material to other countries that can generate sufficient renewable electricity at low costs. These countries would produce PtX products such as green naphtha, which would in turn be imported into NRW. The import options for PtX products are likely to be similar to the options currently available to basic materials produced from fossil resources. The CO_2 infrastructure would likely look very similar to the one presented by the Wuppertal Institute (ibid.). Greenhouse gas neutrality must be ensured by closing global carbon cycles. The likelihood of this option becoming a reality depends largely on how much renewable electricity is available in other countries to produce PtX products and whether these countries can supply themselves with carbon dioxide using DAC (if necessary). Another determining factor will be which method of carbon dioxide supply (import vs DAC) proves more economical.

Option 4: complete production of chemical products at the renewable energy site (renewables pull)

Option 4 differs from option 3 in that not only are intermediate PtX products produced in other countries with cost-effective renewable energy conditions but that the other processing steps are also carried out in these countries.[1] Looking at NRW, this would mean significant change for the products and value chains of the Rhine cluster.

Conclusion:
The previous sections have shown that hugely different needs in terms of CO_2 infrastructure may emerge, particularly with regard to the Rhine cluster. Sound planning will require the creation of reliable frameworks and foundations for new business models, both for the CO_2 emitters of today and tomorrow as well as the parties who will still require carbon in their processes.

CO_2 infrastructure must be planned in good time and made available at the right time, for the transport of CO_2 for both CCS and CCU, to maintain the economic output of NRW and also to achieve climate neutrality in industry.

1 This process is referred to as renewables pull (cf. SCI4climate.NRW 2021b).

5. REQUIRED ACTIONS FOR THE IMPLEMENTATION OF CO_2 INFRASTRUCTURE

Infrastructure planning and preparation must begin as soon as possible on account of long organisational and development lead times. Politics must set the course right away to make it possible for a carbon dioxide economy to emerge, to safeguard the value creation of the affected industries through an appropriate framework and to maintain NRW as a competitive location on the global stage. The economic mechanisms required to create the infrastructure must also be put in place.

At the same time, industry must clarify any unanswered technical questions with the scientific community and develop suitable concepts and projects.

Some tasks, however, can only be completed with all parties from politics, industry and the scientific community working together. The following lists present what the working group on the carbon dioxide economy regards as current inhibitors and recommended actions to remedy these issues.

Joint areas of action

Inhibitors	Recommended actions
Lack of knowledge regarding the acceptance of CO_2 infrastructure and CO_2 storage	• Social acceptance of proposed measures is a prerequisite for any infrastructure construction. This has to be supported with the **timely supply of information and participation procedures.** An informed discourse and suitable communication strategy must be prepared to provide information to various stakeholders (in particular the public and politics) about the requirements and necessities of CO_2 infrastructure and storage.
Lack of communication strategy	The following aspects should be taken into consideration when developing a suitable communication strategy: • **Safety-related aspects** must be addressed. Findings from existing projects (see Port of Rotterdam and Antwerp) may prove useful. • Certain processes will continue to produce CO_2 in the future even if society transitions fully to renewable energy. It is therefore imperative that we find ways to **use and manage** the CO_2 still produced in order to achieve climate neutrality.

- In contrast to carbon capture at coal-fired power stations, carbon capture of unavoidable CO_2 in industrial processes **does not create a lock-in effect** for the use of fossil fuels.
- CCS for unavoidable CO_2 production is an important factor towards achieving **climate neutrality** by 2045.
- CCU is more than just an option to supply CO_2 for further use. It's also a way to **ensure the supply of raw material** in a climate-neutral world.
- When constructing CO_2 infrastructure, efforts should be made to connect it to existing **offshore CO_2 storage** projects.

Lack of planning and implementation of CO_2 infrastructure projects

- **Real-world laboratories** as a jump start for practical projects: a real-world laboratory would help demonstrate the rather neglected but relevant aspects of transporting CO_2, including purification and liquid vs. gas transport. Initial projects transporting limited volumes of CO_2 by rail appear feasible. These would transport CO_2 in and out of NRW, all the way to the North Sea ports in Germany, the Netherlands and Belgian.
- The construction of **CO_2 infrastructure (pipelines)** is the limiting factor in terms of managing large volumes of CO_2. It must be planned and constructed before large volumes of CO_2 are captured.

Various development paths towards climate neutrality (cf. Section 4): some significant differences in infrastructure needs

- Preferably, the infrastructure should be of sufficient size to be able to react accordingly to certain developments. It is therefore important to find an economic trade-off between cost and flexibility. Greater flexibility and capacity go hand in hand with higher costs for CO_2 infrastructure. However, it is important to note that subsequent capacity expansions to gas infrastructure often lead to additional costs that come close to the original investment. Consequently, sustainable infrastructure planning should consider the scenarios of a carbon-neutral economy in NRW from the very start.

Inhibitors	Recommended actions
No national strategy for the development of CO_2 infrastructure	• A **“no-regret” strategy** for the development of CO_2 infrastructure should be drafted and agreed upon with all parties. This should be based on clarification of the CO_2 infrastructure required in each case and drafting a sound strategy that allows for modular expansion of this infrastructure.

Politics

Inhibitors	Recommended actions
Lack of knowledge regarding (local) acceptance of an extensive infrastructure expansion	• The state government of NRW must acknowledge that **CO_2 transport** for CCS and CCU is necessary. • The state government should create and implement ideas for promoting the project which aim to foster **public acceptance**.

Lack of a legal framework hindering the creation of a carbon dioxide economy[2]	• Create a legal framework for CO_2 infrastructure and CCS measures, which should, among other things:
	  • Regulate **EU-ETS** transport via ship and pipeline,
	  • Contain an amendment to the **London Protocol** to make international CCS possible.
	• The state government should support the creation of necessary **planning and regulatory** requirements, e.g., in relation to the Law on the Demonstration of the Permanent Storage of Carbon Dioxide (KSpG). The scope of infrastructure-related regulations should be expanded to include CO_2 transport for CCU purposes.

2 The report commissioned by IN4climate.NRW (Benrath 2021) provides an overview of the current legal framework for a carbon dioxide economy.

Overly complex approval procedures: lack of political safeguards for real-world laboratories	• **Approval procedures for real-world laboratories** should be simplified. Up until now, the procedures have been the same as those for ETS plants:
	  • The necessity of public procedures for real-world laboratories should be called into question. The competent authorities should be given decision-making aids, which make it easier to classify real-world laboratories as **(trial) facilities for research, development or testing processes**, especially with regard to Section 1, para. 6 and Section 2, para. 3 of the 4th German Federal Immission Protection Ordinance (BImSchV).
	  • For the sake of simplification and expedition, real-world laboratories should either be approved as part of a **simplified procedure under the German Federal Immission Control Act (BImSchG)**, instead of a formal procedure (Section 2, para. 3 of the 4th German Federal Immission Protection Ordinance (BImSchV)), or be allowed to be constructed and operated without approval (Section 1, para. 6.).

Lack of economic viability of business models for the carbon dioxide economy under present conditions	• The German Federal government should set out the necessary legal and economic requirements. This applies to questions regarding **validity, accounting and credit eligibility**[3], if CO_2 is fed into or removed from the transport infrastructure as well as the question of possible operating structures (analogue transport network operators, gas/electricity or waste disposal providers). • Both the **input and removal of CO_2** from an infrastructure must be given equal consideration in the planning and creation of the legal framework. Sector coupling should be considered as a possible goal. • **CAPEX and OPEX funding** will be required.

3 The Fit for 55 package (European Commission 2021) stipulates that permanently chemically bound CO_2 can be offset in the EU-ETS. A definition of when CO_2 can be considered "permanently chemically bound", or alternatively a list of eligible CCU products, is still pending.

	• The German Federal government should create **demand incentives** for carbon-neutral products to form a value chain in a carbon dioxide economy. • In order to provide planning security, the EU commission should announce the **development of the EU-ETS** in the second half of the fourth phase from 2026 and from 2031 in good time. This will ensure that the CO_2 price progresses predictably over the long term for all parties and will allow public discussion regarding the topic of a carbon dioxide economy and CO_2 infrastructure to play out. • CCS must be considered in the **TEN-E** regulation.
Lack of planning for CO_2 infrastructure	• A **step-by-step plan** for the introduction and implementation of CO_2 infrastructure in NRW and CCS measures will be required – at the national level but also at the European and international levels too. • **European funding guidelines** for renewable energy and transport systems will need to be adopted. • The German Federal government will need to create a **network development plan** for CO_2 infrastructure by 2023 at the latest.
Lack of renewable energy for CCU	• The high electricity and/or hydrogen demands for CCU should be taken into consideration by both state and federal governments when planning the expansion of renewable energies.
Lack of alternatives to CO_2 intensive products	• Funding is needed for further research into the substitution of products and efficiency in product use with regard to reducing CO_2 volumes produced. Promote the use of CCS alternatives using policy tools.

Business

Inhibitors	Recommended actions
Lack of standards and norms	• **Minimum requirements for CO_2 flows** (that are to be transported and stored) need to be ascertained and laid down in standards.
Lack of concepts for processing CO_2	• **Cross-industry concepts** for processing CO_2 based on specific production locations need to be developed: it needs to be ascertained whether CO_2 should be processed on-site at capture facilities immediately before transport or whether central processing facilities close to several sources of CO_2 are a more sensible option.
Capture technology for certain applications not fully developed	• **Capture technology** should be developed and evaluated, and the findings of ongoing research applied to other fields of application.
Efficiency in the carbon cycle	• In addition to CCS, any and all **alternatives that avoid CO_2 emissions** should be fully exploited in each sector to keep CO_2 volumes as low as possible.
Lack of infrastructure and value chains in Germany	• **Transparency** is required regarding both the schedule for and scaling of CO_2 capture as well as the use of CO_2 as this will allow users, producers, carriers and the competent authorities to form connections and communicate effectively. • Think network – **synergies** in NRW should be used and built upon to launch a carbon dioxide infrastructure and economy. Exploiting local advantages in NRW may help contribute to public acceptance. • Long-term forecasts need to be created together with the scientific community that mark out CO_2 demand for CCU compared to the amounts of CO_2 removed with CCS.

	How this is likely to develop over time needs to be investigated to determine the extent to which certain CCS infrastructure will be needed in the long term.
Lack of a legal and political framework	• Pilot projects and real-world laboratories should be initiated to increase the visibility of the technology and create **blueprints for the definition of "permanently chemically bound"[4] CO_2 for credits in EU-ETS**. • Demonstrate **business models** or the limits of a business case: among other things, the costs of capture but also the value of CO_2 as a raw material in comparison to storage need to be clarified. The entire value chain should be considered to demonstrate at which CO_2 price CCS and CCU become worthwhile and how much energy each requires.

Science

Inhibitors	Recommended actions
Lack of infrastructure concepts	• Studies are needed that assess the step-by-step build-up of infrastructure and **holistic system design** respectively. Feasibility approaches should be applied. • Industry as a whole needs to investigate whether intermediate storage is required. Infrastructure must be amended accordingly if **intermediate storage** is indeed required. A cost-benefit analysis should be performed.
Unknown carbon demand	• **Long-term forecasts** need to be created together with industry that mark out **CO_2 demand** for CCU compared to the amounts of CO_2 removed using CCS.

4 The Fit for 55 package (ibid.) stipulates that permanently chemically bound CO_2 can be offset in the EU-ETS. A definition of when CO_2 can be considered "permanently chemically bound", or alternatively a list of eligible CCU products, is still pending.

	How this is likely to develop over time needs to be investigated to determine the extent to which certain CCS infrastructure will be needed in the long term.
	
	• **Carbon cycle accounting** is needed in addition to ascertaining industrial CO_2 requirements. The cycle must be considered from a global perspective. It may be more effective to start with a smaller area at the beginning: NRW → Germany → Neighbouring Countries → Europe → Global.
	
	• For this reason, **future value chains** and their development over time need to be mapped out. This includes amongst others:
	  • H_2 demand for CCU
	  • Competitive landscape: green crude[5]

Unknown potential of different technologies to act as a carbon sink	• **Recarbonation:** the potential of recarbonation to act as a carbon sink is a given but to what extent and how this might develop over time still needs to be investigated. • The roles of **BECCS** and **DAC** in helping NRW progress towards climate-neutral industry require further investigation.

Capture technology for certain applications not fully developed	• **CO_2 capture technology** needs to be developed further for the different waste gas flows of industry.
Lack of alternatives to CO_2 intensive products	• Further research is needed into the **substitution of products and efficiency in product use** with regard to reducing CO_2 production.
No fully developed CCU path	• **CCU concepts and pathways** need to be developed further and evaluated in terms of energy, economy and ecology.

5 Green crude refers to crude oil that is not based on fossil fuels but rather created from alternative "green" sources.

High standards regarding CO_2 purity and diverse CO_2 sources	• Concepts for **processing CO_2** need to be developed. Appropriate technologies on appropriate scales should be made available as there will be central point sources (e.g., cement plants), but also decentralised sources (e.g., WTE plants and biomass CHP plants), which will need to be used to close the cycle. This also relates to other process steps and technologies in the context of managing CO_2.
No appropriate standards regarding CO_2 purity	• Technical requirements regarding CO_2 purity: use and transport are expected to have different requirements concerning purity. European standards are therefore required. A tiered **quality concept** should be developed.
Lack of knowledge regarding the acceptance of CO_2 infrastructure and CO_2 storage	• Research and development need to be conducted into **current acceptance** among the German populace of CCS and CCU processes, and also of the required CO_2 infrastructure.
Lack of knowledge on business models	• Existing international examples for the use of CCS and CCU need to be investigated to determine, among other things, development, **economic success** and the political frameworks in place in each instance. • New value chains need to be identified and their potential evaluated for CCS and CCU technologies.

BIBLIOGRAPHY

acatech (Ed.) 2018: CCU und CCS – Bausteine für den Klimaschutz in der Industrie. München: Herbert Utz Verlag. acatech POSITION.

ACT Acorn Consortium 2019: D20 Final Report. 10196 ACTC-Rep-35-01. Available online at: https://actacorn.eu/sites/default/files/ACT%20Acorn%20Final%20Report.pdf.

AiF 2020: Kalkbasierter Feststoffreaktor zur CO_2-Abtrennung aus Abgasen mit regenerativ Rückgewinnung der Reaktionsenthalpie (IGF-Projektsteckbrief). AiF Arbeitsgemeinschaft industrieller Forschungsvereinigungen „Otto von Guericke" e. V. Available online at: https://igf.aif.de/innovationsfoerderung/industrielle-gemeinschaftsforschung/igf-steckbrief.php?id=23955&-suchtext= (accesssed on September 28th, 2021).

Arends, Peter 2021: CO_2 reduction through storage beneath the North Sea. Experiences & Challenges. Presented at the ECRA Online Conference 2021.

Benrath, Daniel et al. 2020: CO_2 and H_2 Infrastructure in Germany – Final Report of the German Case Study.

Benrath, Daniel 2021: Rechtliche Rahmenbedingungen einer Kohlendioxidwirtschaft – Gutachten zu Fragestellungen aus der IN4climate.NRW-Arbeitsgruppe Kohlendioxidwirtschaft. Gelsenkirchen: IN4climate.NRW GmbH (Ed.). Available online at: https://www.in4climate.nrw/fileadmin/Nachrichten/2021/Gutachten_KdW/in4climate.nrw-gutachten-ag-kdw-rechtliche-rahmenbedingungen-kohlendioxidwirtschaft.pdf.

BMU 2021: Novelle des Klimaschutzgesetzes vom Bundestag beschlossen. Berlin: Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit. Available online at: https://www.bmu.de/pressemitteilung/novelle-des-klimaschutzgesetzes-vom-bundestag-beschlossen (accesssed on August 9th, 2021).

Brevik, Per 2017: The full scale CCS-project at Norcem Brevik. Can it be realised? Düsseldorf.

Brown, Andy 2021: Solutions for CO_2 pipeline construction in the UK. Presented at the ECRA Online Conference 2021.

BVK (n. d.): Kalk. In: Bundesverband der deutschen Kalkindustrie e. V. Available online at: https://www.kalk.de/klimaschutz/partner (accesssed on August 25th, 2021).

CemNet 2019a: Carbon capture is a loss-maker for Anhui Conch. In: International Cement Review. Available online at: https://www.cemnet.com/News/story/167315/carbon-capture-is-a-loss-maker-for-anhui-conch.html (accesssed on June 11th, 2021).

CemNet 2019b: LEILAC 2 is in the pipeline. In: International Cement Review. Available online at: https://www.cemnet.com/News/story/167975/leilac-2-is-in-the-pipeline.html (accessed on June 11th, 2021).

DECHEMA (n. d.): NuKoS – Nutzung von Kohlenstoffdioxid in Schlacken aus Stahl- und Metallproduktion. In: CO_2-Win. Available online at: https://co2-utilization.net/de/projekte/co2-mineralisation/nukos/ (accesssed on September 2nd, 2021).

Deerberg, Görge; Oles, Markus; Schlögl, Robert 2018: The Project Carbon2Chem. In: Chemie Ingenieur Technik 90 (10), S. 1365–1368.

ECRA 2020: Creating value chains for CO_2 capture, transport, storage and use. In: ECRA-Newsletter (2), S. 3–4.

ECRA, CSI 2017: Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead; CSI/ECRA-Technology Papers 2017. Düsseldorf, Geneva: European Cement Research Academy; Cement Sustainability Initiative (Ed.). Available online at: https://ecra-online.org/research/technology-papers/.

EuLa (n. d.): Lime as a natural carbon sink - Examples of mineral carbonation in lime applications. Brüssel: European Lime Association. Available online at: https://www.eula.eu/politecnico-di-milano-literature-review-on-the-assessment-of-the-carbonation-potential-of-lime-in-different-markets-and-beyond/.

European Commission 2021: Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757. Available online at: https://ec.europa.eu/info/sites/default/files/revision-eu-ets_with-annex_en_0.pdf.

GFZ 2004: CO_2SINK und CO_2 des deutschen Geoforschungszentrums. Available online at: https://www.co2ketzin.de/ (accesssed on September 28th, 2021).

Global CCS Institute 2020: Global Status of CCS: 2020. Australien.

Grosso, Mario et al. 2020: Literature review on the assessment of the carbonation potential of lime in different markets and beyond. Report prepared by Assessment on Waste and Resources (AWARE) Research Group at Politecnico di Milano (PoliMI), for the European Lime Association (EuLA). Pp. 333.

Hoenig, Volker et al. 2012: ECRA CCS Project – Report on Phase III. Technical Report TR-ECRA-119/2012. Düsseldorf: European Cement Research Academy. Available online at: https://ecra-online.org/research/ccs/.

IEAGHG 2013: Deployment of CCS in the Cement Industry, 2013/19. Cheltenham, UK: International Energy Agency. Available online at: https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1016-2013-19-deployment-of-ccs-in-the-cement-industry.

IN4climate.NRW (Ed.) 2020: Unvermeidbare CO_2-Entstehung in einer klimaneutralen Grundstoffindustrie NRW: Definition und Kriterien. Ein Diskussionsbeitrag der AG Kohlendioxidwirtschaft von IN4climate.NRW. Gelsenkirchen. Available online at: https://www.in4climate.nrw/fileadmin/Nachrichten/2020/Diskussionspapier_Unvermeidbare_CO2_Entstehung/in4climatenrw-diskussionspapier-unvermeidbare-co2-entstehung-web.pdf.

ISO/TR 27912:2016(en): Carbon dioxide capture — Carbon dioxide capture systems, technologies and processes. Available online at: https://www.iso.org/obp/ui/#iso:std:iso:tr:27912:ed-1:v1:en.

ISO/TR 27913:2016(en): Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems. Available online at: https://www.iso.org/obp/ui/#iso:std:iso:27913:ed-1:v1:en.

ISO/TR 27921:2020(en): Carbon dioxide capture, transportation, and geological storage — Cross Cutting Issues — CO_2 stream composition. Available online at: https://www.iso.org/obp/ui/#iso:std:iso:tr:27921:ed-1:v1:en.

ISO/TR 27922:2021(en): Carbon dioxide capture — Overview of carbon dioxide capture technologies in the cement industry. Available online at: https://www.iso.org/obp/ui/#iso:std:iso:tr:27922:ed-1:v1:en.

Kätelhön, Arne et al. 2019: Climate change mitigation potential of carbon capture and utilization in the chemical industry. In: PNAS 116 (23), S. 11187–11194.

Knopf, Stefan et al. 2010: Neuberechnung möglicher Kapazitäten zur CO_2-Speicherung in tiefen Aquifer-Strukturen. In: ENERGIEWIRTSCHAFTLICHE TAGESFRAGE (4), S. 76–80.

LEAP (n. d.): CLEANKER is a project addressing CO_2 capture from cement production. Available online at: http://www.cleanker.eu (accesssed on June 11th, 2021).

Leeson, D. et al. 2017: A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refiningand pulp and paper industries, as well as other high purity sources. In: International Journal of Greenhouse Gas Control (61), S. 71–84.

LEILAC Project (n. d.): Low Emissions Intensity Lime & Cement - LEILAC. Available online at: https://www.project-leilac.eu (accesssed on June 11th, 2021).

Northern Lights (n. d.): What we do. In: Northern Lights. Available online at: https://northernlightsccs.com/what-we-do/ (accesssed on June 11th, 2021).

Otto, Alexander; Markewitz, Peter; Robinius, Martin 2017: Technologiebericht 2.4 CO_2-Nutzung. Wuppertal, Karlsruhe, Saarbrücken: Wuppertal Institut, ISI, IZES (Ed.). Technologien für die Energiewende. Teilbericht 2 an das Bundesministerium für Wirtschaft und Energie (BMWi).

Porthos (n. d.): Project. In: Porthos. Available online at: https://www.porthosco2.nl/en/project/ (accesssed on June 11th, 2021).

Prognos; Öko-Institut; Wuppertal-Institut 2020: Klimaneutrales Deutschland. Studie im Auftrag von Agora Energiewende, Agora Verkehrswende und Stiftung Klimaneutralität.

Rocha, Paulo 2021: Strategy CCUS. Presented at the ECRA Online Conference 2021.

Ruban, Sidonie 2021: From capture to storage - CO_2 cryogenic technologies and logistic chain. Presented by Air Liquide at the ECRA Online Conference 2021.

Ruppert, Johannes et al. 2019: Prozesskettenorientierte Ermittlung der Material- und Energieeffizienzpotentiale in der Zementindustrie: Abschlussbericht (UFOPLAN FKZ 3716 36 320 0). Düsseldorf: VDZ. Available online at: https://www.vdz-online.de/wissensportal/publikationen/abschlussbericht-prozesskettenorientierte-ermittlung-der-material-und-energieeffizienzpotentiale-in-der-zementindustrie.

SCI4climate.NRW 2021a: CO_2-Entstehung der Industrie in einem klimaneutralen NRW Impuls für eine Infrastrukturgestaltung. Available online at: https://www.in4climate.nrw/fileadmin/Downloads/Ergebnisse/SCI4climate.NRW/Szenarien/2020/co2-entstehung-der-industrie-in-einem-klimaneutralen-nrw-impuls-fu%CC%88r-eine-infrastrukturgestaltung-cr-sci4climatenrw.pdf.

SCI4climate.NRW 2021b: Konzeptualisierung des möglichen Renewables-Pull-Phänomens - Definition, Wirkmechanismen und Abgrenzung zu Carbon Leakage. Wuppertal. Available online at: https://www.in4climate.nrw/fileadmin/Downloads/Ergebnisse/SCI4climate.NRW/Szenarien/2020/konzeptualisierung-des-m%C3%B6glichen-renewables-pull-ph%C3%A4nomens-cr-sci4climatenrw.pdf.

Smit, Martijn 2021: Northern Lights. A European CO_2 transport and storage network. Presented at the ECRA Online Conference 2021.

TCC 2017: Corporate Sustainability Report. Taiwan Cement Corporation. Available online at: https://media.taiwancement.com/web_tcc/en/report/csr/report_2017.pdf.

Tenova HYL; Danieli; S.p.A. 2020: Unmatchable Performances and Sustainable Decrease of CO_2 Emissions in Steelmaking. LCF Webinar.

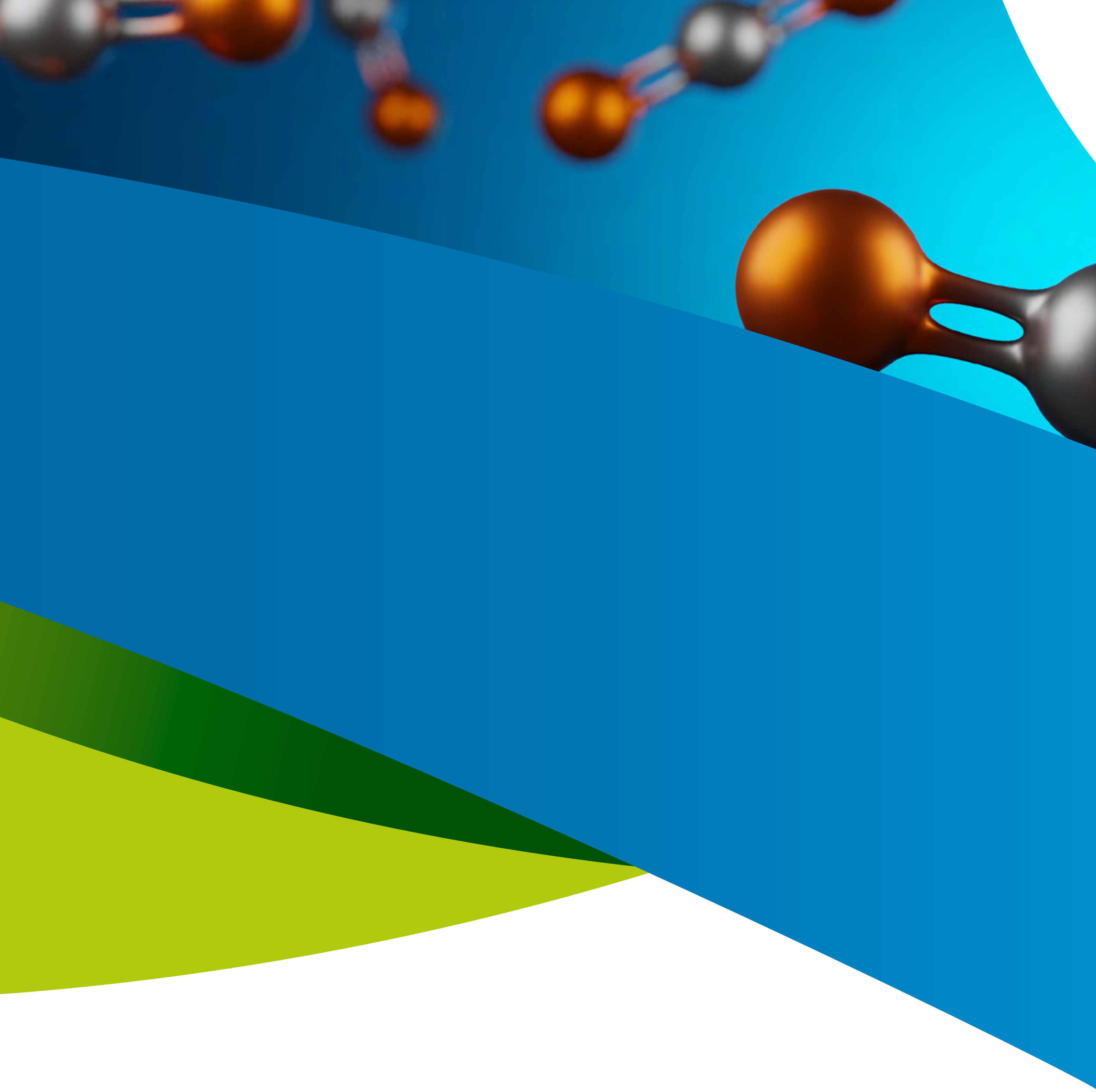
The Stepwise SEWGS Project (n. d.): STEPWISE. Available online at: https://www.stepwise.eu/ (accesssed on June 11th, 2021).

Thomas, Emily 2019: Cement producers have founded an oxyfuel research corporation. In: World Cement. Available online at: https://www.worldcement.com/europe-cis/11122019/cement-producers-have-founded-an-oxyfuel-research-corporation/ (accesssed on June 11th, 2021).

VDZ 2020: Dekarbonisierung von Zement und Beton – Minderungspfade und Handlungsstrategien. Eine CO_2-Roadmap für die deutsche Zementindustrie. Düsseldorf: Verein Deutscher Zementwerke e.V.

VDZ (Ed.) 2019: CO_2-Infrastruktur in NRW – Workshop am 22. August 2019 in Düsseldorf. Available online at: https://www.vdz-online.de/wissensportal/veranstaltungen/co2-infrastruktur-in-nrw.

ZEP 2021: CCS/CCU projects. In: Zero Emissions Platform. Available online at: https://zeroemissionsplatform.eu/about-ccs-ccu/css-ccu-projects/ (accesssed on July 28th, 2021).



IN4
CLIMATE
.NRW

Contact: **IN4climate.NRW**
Munscheidstraße 14
45886 Gelsenkirchen
GERMANY
+49 209 40 85 99-0
post@in4climate.nrw
www.in4climate.nrw/en