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Towards a Climate-Neutral Basic Materials Industry in North Rhine-Westphalia

Stefan Herrig[1*], Iris Rieth[1], Tania Begemann[1], Michael Walther[1], Anna Leipprand[2]

1 NRW.Energy4Climate, Kaistraße 5, 40221 Düsseldorf, Germany
(*Corresponding Author: stefan.herrig@energy4climate.nrw)

2 Wuppertal Institute for Climate, Environment and Energy, Döppersberg 19, 42103 Wuppertal, Germany

ABSTRACT

North Rhine-Westphalia (NRW) is the industrial center of Germany and one of the most important industrial locations in Europe. It is a key location for the energy-intensive basic materials industry like the production of steel and non-ferrous metals, (petro)chemicals, cement and lime, bricks, glass and ceramics, and paper. Around 20 % of NRW's total greenhouse emissions derive from industrial processes. By 2045, industry must achieve climate-neutrality, which requires a massive transformation effort. Technologically, this needs large-scale utilization of green hydrogen, carbon management, consequent circular economy, and climate-neutral production of process heat. Furthermore, various adjustments to the policy framework are essential.

Keywords: industry transformation, climate-neutral industry, hydrogen, carbon management, circular economy, process heat

NOMENCLATURE

Abbreviations	
BECCS	Bioenergy with carbon capture and storage
CCfD	Carbon Contracts for Difference
CCU	Carbon capture and utilization
CCS	Carbon capture and storage
EU ETS	European Emissions Trading System
NRW	North Rhine-Westphalia

1. INTRODUCTION

North Rhine-Westphalia (NRW) is the industrial center of Germany and one of the most important industrial locations in Europe. More than 1.22 million people work here in over 10,000 industrial companies. This means that around 20 % of the employees work in industry. In addition, many are employed by service companies and thus work indirectly in industry. In 2021, annual sales of around 357 billion euros were generated [1]. Hence, almost every fifth euro of the German industrial sales is generated in North Rhine-Westphalia. NRW is particularly important as a location for the energy-intensive basic materials industry like the production of steel and non-ferrous metals, (petro)chemicals, cement and lime, bricks, glass and ceramics, and paper. 50 % of the German and 10 % of the European production sites of these industries are in NRW [2].

North Rhine-Westphalia's industry faces enormous challenges: maintaining and expanding the important industrial center must be combined with achieving the national and global climate protection goals. Between 1990 and 2019, NRW's industry has already reduced its emissions by around 40 million tons of CO_2-equivalents, from 94.3 million tons to 51.2 million tons. Nevertheless, around 20 % of the state's total greenhouse gas emissions still come from industrial processes [3]. In the interests of climate protection, these emissions must be reduced more significantly and avoided completely in the future. The NRW state government has committed itself to the goal of climate neutrality for the year 2045, which naturally also applies to the industrial sector. This is particularly challenging because many companies operate internationally and offer their products in competition with companies in other European and global countries. These competitors often produce under weaker climate and environmental protection requirements and thus more cost-effectively. This creates the risk of carbon leakage effects through the relocation of former NRW production sites to such locations. To avoid this, industrial processes must be rethought, and innovative technologies and strategies developed that combine climate protection and competitiveness in NRW. The course for this transformation must be set today. About 50 % of the central industrial plants of the German basic materials industry need to be renewed or extensively revised in the next ten years [4]. Many of these plants, such as float glass furnaces, last up to 10, 15, or more years. Thus, plants that are renewed in 2025 might run until 2040 and are therefore crucial on the path to climate neutrality.

In 2019, the Ministry of Economic Affairs, Innovation, Digitalization and Energy of NRW launched the think tank "IN4climate.NRW", an interdisciplinary and cross-industry working platform focussing on the transformation of the energy-intensive basic materials industry sector. The most important players from these industries are working together with renowned research institutes (as part of the associated research project "SCI4climate.NRW") and political representatives to discuss and develop technology paths towards climate neutrality (see Sec. 2) as well as necessary adjustments to the policy framework (see Sec. 3).

2. TECHNOLOGY PATHS FOR INDUSTRY TRANSFORMATION

2.1 Green Hydrogen

A climate-neutral basic materials industry is impossible without the use of green hydrogen produced by electrolysis with renewable electricity. Hydrogen will be essential in two ways: as a carbon-free energy carrier and as feedstock in the (petro)chemical industry.

As an energy carrier, it will be used in particular in processes that cannot be made climate-neutral technically or economically by direct electrification with electricity from renewable energies. This applies especially to processes with high heat demand at high temperature levels. For the cement industry, no large-scale electrically heated rotary kilns are yet available. According to the current state of technology it is also not possible to electrically heat large float glass furnaces. In brick production, the surface finish and color are defined by the combustion chamber atmosphere. Additionally, the products of many metal processing plants like for example large-scale forges are too large or have too complex geometries to be heated electrically.

There is already a considerable demand for hydrogen as feedstock in NRW's petrochemical and chemical industry (especially for ammonia and methanol synthesis). However, up till now it is almost completely covered by gray hydrogen from reformation of natural gas. To reduce CO_2 emissions in the chemical industry, gray hydrogen must be completely replaced in the long term by green hydrogen. The green hydrogen demand may increase considerably if refineries in NRW will produce synthetic fuels on a large scale in the future.

However, the biggest driver for a future North Rhine-Westphalian hydrogen economy is the steel industry. In NRW, 16 million tons of crude steel are produced, which accounts for 38 % of the total production in Germany. Duisburg is home to the largest steel production site in Europe [5]. Most of the steel is produced via the classic blast furnace route, emitting large amounts of CO_2. In fact, the iron and steel industries emit more than 40 % of the CO_2 emissions of NRW's industry [3]. An alternative to the classic blast furnace route is the electric arc process with steel scrap as the main input material. However, the future contribution of secondary steel produced in this process to the total steel production is limited, firstly because it is not possible to produce sufficiently high-quality steels in this way for all purposes and secondly because of the limited availability of scrap. In order to produce high-quality steel in a climate-neutral way in NRW the production will have to be switched to hydrogen direct reduction. In this process, hydrogen is used as a reducing agent for the ore instead of coke and injected coal. Thus, hydrogen is both energy carrier and, to a certain extent, also feedstock in the process. The product of hydrogen direct reduction is solid direct reduced iron, which is then processed into crude steel in electric melting furnaces and the subsequent converter. The switch to hydrogen direct reduction will result in an enormous hydrogen demand in NRW. For a completely climate-neutral production thyssenkrupp Steel is expecting a hydrogen demand of more than 700,000 tons per year.

In the Hydrogen Roadmap North Rhine-Westphalia, a total hydrogen demand of about 104 TWh per year is expected [6]. This high demand will turn NRW into one of the most important centers of a future European hydrogen economy requiring a large-scale hydrogen infrastructure as well as import cooperation with potential European and worldwide import countries (see Fig. 1). During the ramp-up phase of this hydrogen economy, various "chicken-and-egg" problems need to be solved to synchronize the development of the industrial demand, infrastructure build-up and investments in H_2-ready technologies. This turns the elaboration of a suitable policy framework (see Sec. 3) into a highly complex task. With the publication of its hydrogen roadmap, the NRW state government has taken a first important step towards setting the course defining clear targets for hydrogen production, infrastructure, and utilization projects in the years 2025 and 2030 [6].

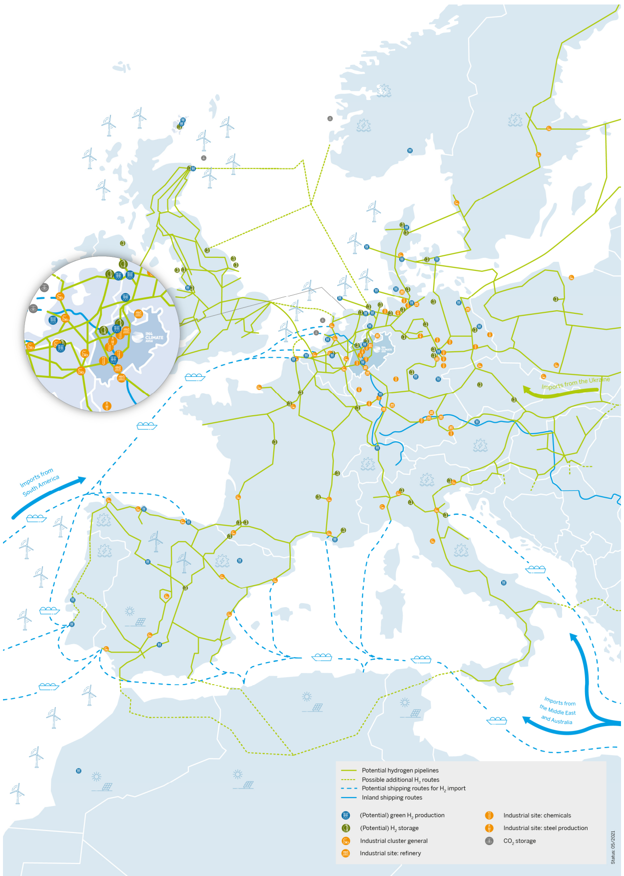

Fig. 1 Vision of NRW as a part of a future European hydrogen economy developed in IN4climate.NRW based on intensive research on hydrogen infrastructure, production and utilization projects proposed by various European players.

2.2 Carbon Management

By consequently using renewable energy sources and alternative fuels such as green hydrogen (as discussed in Sec. 2.1), (fossil) carbon can largely be substituted for energy production. However, carbon is also widely used as an important industrial raw material and auxiliary substance leading to so-called process-related CO_2 emissions. With the technical progress predictable today, there will hence still be unavoidable amounts of CO_2 produced in the basic materials industry in 2045 [7]. In 2021, NRW became the first German state to present a carbon management strategy. At the German federal level, such a strategy is not yet available. According to the Carbon Management Strategy North Rhine-Westphalia [8], the process-related production of CO_2 is considered unavoidable if no alternative raw materials and processes are available to produce the requested end product, with technical feasibility as well as systemic aspects, such as the availability of renewable energies or green hydrogen, being included in the assessment. Due to its strong basic materials industry, it can be assumed that there will still be considerable point sources of unavoidable CO_2 amounts in NRW in the future - especially at production sites of the glass, chemical, lime and cement industries and in parts also of the steel industry. Carbon capture plants must be installed at these unavoidable point sources and the captured CO_2 must either be transported to utilization applications (carbon capture and utilization, CCU) or to long-term geological storage sites (carbon capture and storage, CCS).

It must be clarified that a complete decarbonization of the industrial sector is not possible and not requested. Without carbon there is no production of steel, cement, glass, or basic chemicals. CCU allows CO_2, or carbon, to be used in cycles to cover the industrial carbon demand when fossil carbon sources will be completely omitted in a climate-neutral industry. Thus, CCU will be one element of a consequent circular economy in industry that will be crucial in the future (see Sec. 2.3).

CCS enables CO_2 to be removed from the carbon cycle through the long-term storage in geological reservoirs. By means of CCS, production processes can achieve climate neutrality despite unavoidable process-related CO_2 amounts. The current social acceptance of CCS in Germany has hardly been studied. However, it is probably low, in particular for CO_2 storage in Germany. Nevertheless, the Carbon Management Strategy of North Rhine-Westphalia is clear about the importance of CCS for the industry sector: there will not be a climate-neutral industry without CCS [8]. If the use of biomass as an energy source for industry is combined with CCS, so-called negative emissions can also be realized (referred to as bioenergy with carbon capture and storage, BECCS). Some studies consider this technology path indispensable to achieve climate neutrality [4, 7]

The Carbon Management Strategy North Rhine-Westphalia foresees the parallel implementation of the necessary preconditions for CCU and CCS. This includes the suitable policy framework (see Sec. 3), the social discourse as well as the implementation of capture technologies and the development of a CO_2 infrastructure [8]. A concept for a first North Rhine-Westphalian CO_2 infrastructure was developed in the research project SCI4climate.NRW and is shown in Fig. 2 [7]. The infrastructure is focused on two important clusters: (1) the Rhine cluster with the chemistry parks in Wesseling and Dormagen and additionally the Ruhr area mainly with its chemical and steel industry, and (2) the Westphalia cluster with its lime and cement industry.

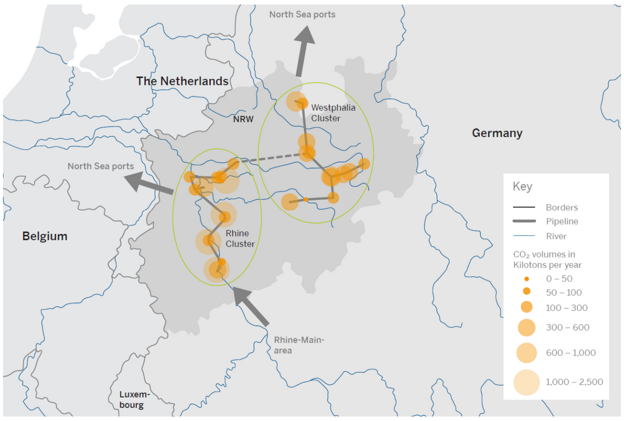

Fig. 2 Concept for a CO_2 pipeline infrastructure for the Rhine and Westphalia cluster in a climate-neutral industry, including possible connections and cross-connections (dashed) as proposed by SCI4climate.NRW [7].

The question, however, is not only how to deal with unavoidable amounts of CO_2, but also how to shift the feedstock base to non-fossil carbon sources. The basic materials industry's carbon needs are not expected to be covered by CCU. Therefore, new sustainable carbon sources will have to be developed and production processes converted. The sustainability of such alternative value chains should not only be evaluated based on the carbon footprint but also based on the energy balance, the possible additional hydrogen demand (as feedstock), as well as the product quality and environmental compatibility. Taking these criteria into account, secondary raw materials and biogenic residual and waste materials can also be sustainable carbon sources in addition to CO_2 from unavoidable point sources.

Carbon management is essential for the transformation of the primary industry in NRW. The key requirements of the strategy are in a nutshell:

1. Decarbonization: replacing carbon where possible
2. Defossilization: switching to sustainable carbon sources
    a. Utilization of secondary raw materials (recycling)
    b. CCU and utilization of biomass
3. CCS as the last element for climate neutrality

2.3 Circular Economy

IN4climate.NRW and the associated research project SCI4climate.NRW have done extensive research on circular economy in a climate-neutral basic materials industry and have published several papers on it, for example [9] and [10]. The brief outline on this subject given in this section is widely based on these publications.

Circular economy strategies such as reuse, remanufacture and design for recycling already exist for the downstream value chain. But some basic materials industries face the challenge of shifting to new sources of raw materials and of ultimately closing the material loop. In the basic materials industry, primary raw materials can be replaced by secondary raw materials with the help of two complementary strategies: (1) recycling of pre- and post-consumer waste and (2) cross-industry utilization of residual materials and by-products from other basic materials industries. The use of secondary raw materials as a key element of circular economy has the potential to reduce CO_2 emissions from the production of new basic materials.

New collection, separation and recycling technologies are important sources of leverage when it comes to increasing a circular economy based on high-quality recycling. Specific approaches need to be further developed primarily related to separation, for example separation of plastics according to type; precision separation of aluminum scrap into alloys; improved separation of metallic and organic components for steel recycling; separation of coarse aggregates, sand, and hydrated cement in concrete recycling; and separating out ultra-fine particles for glass recycling. In addition, research and development on the industrial upscaling of innovative recycling processes like the chemical recycling of plastics are needed (see [10]). The importance of chemical recycling for a climate-neutral plastics industry is illustrated in Fig. 3.

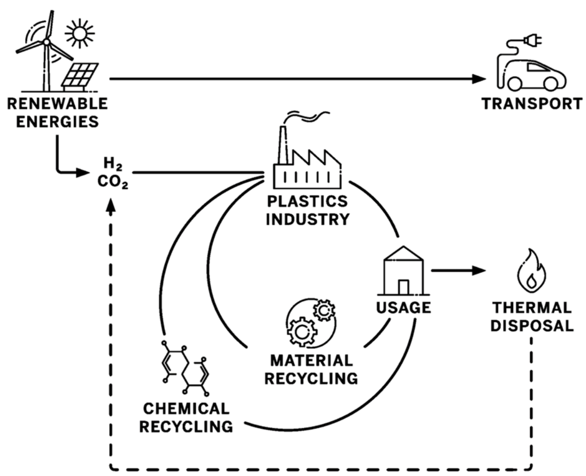

Fig. 3 Concept for a future circular economy in the plastics industry as proposed by IN4climate.NRW [10].

Adapting these strategies to existing production processes is not the only challenge for the basic materials industry related to the realization of a consequent circular economy. It will also have to cope with changes to its material streams (input and output) as part of the industrial transformation towards climate neutrality. There is already a need to develop concepts to maintain and further expand the existing industrial symbioses by incorporating new material streams [9].

2.4 Climate-Neutral Generation of Process Heat

In this section, the climate-neutral generation of process heat is discussed specifically because this important element of the industrial transformation and the energy transition in general is often considered poorly in other studies. Process heat accounts for 67 % of the energy consumption in the German industry and thus for almost 20 % of the total German energy demand [11]. This is not surprising, since glass, metal, cement, or paper must be melted, forged, fired or dried. All these processes require process heat - in some cases up to a temperature of 3,000 °C. In addition, large amounts of process-related heat are required in chemical processes, for example to enable reactions. Thus, an industrial heat transition is crucial to achieve climate neutrality. With the help of its industry partners, IN4climate.NRW has compiled and evaluated future technology options for climate-neutral process heat generation on different temperature levels [12]. Recommendations for the transformation process were derived from these options and summarized in a four-step model. The prioritization in this model results from the decreasing total system efficiency considering losses in the conversion chains:

1. **„Efficiency First“:** Heat that does not have to be produced at all, has the best greenhouse gas footprint. Thus, enhancing efficiency should be considered first. This can be done by reducing the process heat demand through process optimization (for example, by heat dimming enhancement or heat-recovery), as well as the reduction of heat temperature levels. Other options to increase efficiency and overall process performance are the internal (possibly by means of high-temperature heat pumps) and external waste heat utilization (for example, for district heating), as well as the conversion of waste heat to electricity.
2. **Utilization of local renewable heat sources**: Concentrated solar thermal energy and deep geothermal heat can contribute to process heat supply. Even though achievable temperatures are limited, there are various possible applications. The integration of renewable heat sources also reduces the dependence on energy imports and on the associated price volatility. Another important advantage of deep geothermal energy is its continuous availability which makes it capable for base load.
3. **Electrification of process heat production**: Due to the higher overall systemic efficiency, power-to-heat with green electricity should be preferred to using alternative energy carriers such as green hydrogen or synthetic methane. Many electrical systems for the basic materials industry are already available on the market, for example electric arc furnaces, inductive heating systems, electric or electrode boilers, and heat pumps. Due to the volatile availability of green electricity, electrification of process heat will in many cases require the addition of thermal energy storages.
   At this point, it should be highlighted again that renewable power generation and a solid related infrastructure are basic prerequisites for a climate-neutral future, not only for the industrial sector but also for mobility and building heating.
4. **Utilization of alternative (and storable) energy carriers** (green hydrogen, biomass, synthetic methane): Even in a carbon-neutral industry, some processes will require the combustion of energy carriers (as discussed in Sec. 2.1). However, their use should be limited to these processes. Otherwise, conversion losses will increase the overall energy demand of the industrial sector. Furthermore, the combustion of synthetic methane or biomass releases CO_2 that cannot necessarily be regarded as climate neutral. The use of carbon-free energy carriers should be prioritized to promote decarbonization in industry.

3. POLICY FRAMEWORK AS A KEY CHALLENGE

The industry transformation in North Rhine-Westphalia needs a policy framework that facilitates the deployment of the different technology paths and strategies presented in Sections 2.1 to 2.4. It should enable the shift to new low-carbon production processes, facilitate the emergence of a more circular economy, and ensure the supply of sufficient amounts of green energy including green hydrogen. International competitiveness needs to be preserved, and the distribution of transformation costs needs to be negotiated between producers, consumers, and government budgets. Several policy measures in a package can address these different requirements. The following policy instruments are considered as key components:

- **Carbon pricing** is key to ensure that external costs are internalized and that low-carbon production becomes economically competitive. The European Emissions Trading System (EU ETS) provides this systemic shift in price signals for NRW's industry. Through several reforms since its introduction in 2005, the EU ETS has been strengthened considerably, so that today it creates meaningful CO_2 price signals. The European Commission and the European Parliament have proposed new reforms for the EU ETS in the context of the EU's Fit for 55 policy package that would further strengthen the system and adjust it to the stepped-up EU greenhouse gas reduction targets. It is important that ambition is preserved in the upcoming negotiations with the Council of the EU.
- **Support instruments** may nevertheless be necessary temporarily to create business cases and promote the roll-out of new technologies in the short term. In many cases the CO_2 avoidance costs of low-carbon technologies for industry are still higher than CO_2 prices, or uncertainty in CO_2 price developments is a barrier to investment. Instruments such as Carbon Contracts for Difference (CCfD) help to enable the shift to new technologies early enough to avoid further lock-in.
- The transformation of industry will be associated with large additional demand for renewable electricity, renewable heat and green hydrogen. Policies thus need to promote **renewable energy production, accessibility of renewable heat resources, production and import of clean hydrogen**, the build-up of necessary **infrastructures for electricity and hydrogen,** and ideally **heating networks**. For this, adjustments in renewable energy targets and support schemes for renewables, new import programs, reforms to grid infrastructure planning, integrated planning of gas and electricity grids, and simplification and acceleration of permission procedures are necessary, both at national and European level.
- To achieve climate-neutrality in industry, political strategies for **carbon management** need to be developed, the development of necessary CO_2 transport infrastructures needs to be supported, and both regulation and funding policies need to be adjusted.
- To ensure a smooth transition, mechanisms for **carbon leakage protection** must be in place for conventional production.
- **Markets for low-carbon basic materials and consumer products** need to be created. This requires that information about emissions embedded in the products be made available to actors along the value chain and to consumers. Assessment criteria and labeling systems need to be developed and, ideally, harmonized internationally in order to facilitate marketing of products as climate-friendly or climate-neutral. Standards for public procurement or general product standards can help ensure sufficient and growing demand for these products.

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