CO_2 Utilization in North Rhine-Westphalia

- A feasibility study to accelerate implementation -

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Contents

1 Executive Summary

Scope

North Rhine-Westphalia (NRW) represents the industrial core region of Germany, generating the highest gross domestic product of all the federal states. Currently, a structural change caused by the coal exit plan in the lignite coal producing area mainly between Aachen, Düsseldorf and Bonn comes on top of the ongoing structural changes initiated in the past with the closure of deep coal mining area at the end of 2018. This is on one side a challenge, but on the other side, an opportunity to develop and invest into new technologies, which might support the industrial region from an economic and an employment perspective.

This study assesses the potential of CO_2 utilization (CCU) opportunities not only to recycle carbon and to reduce GHG emissions, but also to sustain and strengthen the local industry and to establish new local industries based on sustainable technologies. Most commodities, which are carbon based, are currently of fossil origin or facing other sustainability challenges. Therefore, the focus of this study is to identify the potential of CO_2-based chemicals, fuels and alternative protein sources.

The report is split in three parts A, B and C. The first part A assesses the infrastructure in NRW and is followed by part B, which analyses potential CCU options in the region with a ranking. Part C performs a detailed case study of the most promising ideas including an economic evaluation. The key results of each part are summarized below.

Results

Part A: Assessment of NRW Infrastructure

- NRW is the industrial core region of Germany, generating the highest gross domestic product of the federal states. About 20% of the working population is employed in the industry sector, generating approx. 27% of the gross value added. The agricultural sector is contributing about 17% of the gross value added.
- The core focus of this study is the Rheinisches Revier, which is located in the southwest of the Rhineland. It is currently a core region for lignite mining and power plants.
- The installed electrical capacity in NRW is about 41 GW, with the major contributors being lignite (10.7 GW), natural gas (8.4 GW), hard coal (6.5 GW), on-shore wind (5.8 GW) and solar (5.2 GW). The Rhine area is dominated by lignite-fired power stations, while gas and hard coal power plants are located in the remaining parts of NRW.[1] The net electricity demand is caused to 51% by the industry, 27% by households, 20% by businesses and 1.6% by the transport sector.[2]
- Throughout NRW, there are 13 chemical parks, mainly located close to the river Rhine or in the northern Ruhr area. Additional chemical facilities are situated outside of the chemical parks.

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[1] https://www.umweltbundesamt.de/bild/kraftwerke-windleistung-in-deutschland, accessed 23.09.2021

[2] https://www.energieatlas.nrw.de/site/werkzeuge/energiestatistik, accessed 23.09.2021

- There are two refinery sites located in NRW: Shell in the Cologne area and BP in the Gelsenkirchen area. They represent the two of the three largest refinery sites in Germany, with a combined processing capacity of 30 million t/a of crude oil and a combined workforce of about 4,900 employees. Pipeline networks are connected to Rotterdam, Wilhelmshaven/Hamburg and Frankfurt/Ludwigshafen areas.
- About 16 million t/a of raw steel are produced in NRW (38 % of total steel production in Germany) and about 45,000 people are employed in this industry.[3] Duisburg is the largest steel site within Europe. NRW-based companies contribute approximately a quarter to the German turnover in non-iron metal production and processing. Almost half of the German steel and metal processing companies produce in NRW.
- The major amount of goods is transported via road, accounting for 79% of transported weight in Germany in 2018. Next to road traffic, the transportation via railway (8.5% of transported weight in 2018), inland waterways (4.2% transported weight in 2018) and sea transport (6.3% transported weight in 2018), and to smaller extent air freight (0.1% of transported weight in 2018) are of importance in Germany.[4]
- A European-wide pipeline network for natural gas exists, with a dense structure in the Rheinisches Revier and Ruhr area. The gas pipeline operators propose future network capacity expansion for the years 2020 to 2030 in the "Netzentwicklungsplan Gas" based on two gas demand scenarios for Germany.
- Currently, Air Liquide operates the longest hydrogen pipeline network in Germany originating at the chemical park in Marl with a length of 240 km, connecting to Castrop-Rauxel and to Leverkusen via Bottrop, Duisburg and Düsseldorf. A 5,900 km long pipeline between Lingen and Gelsenkirchen is planned by the initiative GET H2. The pipeline currently transports natural gas and is operated by Nowega and OGE, which will switch to hydrogen transport by 2023, providing green hydrogen to NRW.
- Nearly half of NRW's territory is used as agricultural land (1.45 million ha). This agricultural land consists of 72% farmland, 27% grassland and only 1% for permanent crops.[5] Livestock has a significant role in NRW, with poultry and pigs being the major livestock. Nearly 4 million tons of animal feed are produced in NRW per year, consisting of locally produced and imported components. The state NRW is the second biggest forage producer in Germany. Over 40,000 companies are involved in the forage production in NRW.[6]

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[3] https://www.wirtschaft.nrw/stahl-und-metalle, accessed 23.09.2021

[4] https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Gueterverkehr/Tabellen/gueterbefoerderung-lr.html, accessed 23.09.2021

[5] https://www.umwelt.nrw.de/landwirtschaft/acker-und-gartenbau, accessed 23.09.2021

[6] https://www.umwelt.nrw.de/landwirtschaft/tierhaltung-und-tierschutz/nutztierhaltung/futtermittel, accessed 23.09.2021

Part B: CCU Idea Ranking

- The criteria to compare the different processes were collected through a literature review and internal discussions. A separation into five groups was done including the following aspects: Technical, infrastructure, environmental compatibility, economic feasibility and rollout scenario. Sub-criteria were used within these groups for further breakdown summing up to a total of 21 sub-criteria. The respective scoring guide can be found in section 5.1.
- A comparative life cycle assessment (LCA) was performed to identify the reduction potential of CO_2-equivalent (CO_2-eq) emissions for each CCU process relative to the conventional production process.
- The life cycle assessment of the different CCU ideas was based on the same parameters for required utilities to ensure comparability. Additionally, two scenarios highlight the effect of selecting different sources for CO_2, H_2, electricity and heat supply on the global warming potential and toxicity impact for both the CCU and conventional processes. The "current" scenario describes the production with current state-of-the-art boundary conditions, i.e., H_2 via steam methane reforming[7], CO_2 capture with amine-scrubbing from cement plant off-gas[8], German electricity mix[9], and heat provided by a market mix of natural gas, oil, coal and biogas[93]. In contrast, the "green Future" scenario applies boundary conditions, which promise lower greenhouse gas emissions: H_2 from PEM electrolyzer[10], CO_2 by direct air capture[11], an electricity mix according to the "revolution scenario" for 2050 by EWI study[12], and heat supplied by electricity. The assumed electricity mix is composed of wind power (59%) and PV (22%), but also gas power (10%). This study considers electrical energy being supplied via the grid to avoid impacts on intermittency or other limiting factors of renewable energy sources.
- Social and public acceptance towards new technologies is crucial for their successful implementation. Several topics in the past have shown how the lack of caring in time for public awareness and social acceptance have delayed or even prevented new technologies' roll-out. One well known example is the "not in my backyard" issue with wind turbine installations while in general renewable energy experiences high acceptance[13]. The major

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[7] Mehmet et al., 2018, Life cycle assessment and water footprint of hydrogen production methods: from conventional to emerging technologies, environments

[8] Müller et al., 2020, The carbon footprint of the carbon feedstock CO_2, Energy & Environmental Science

[9] ecoinvent 3.7 cutoff; market mix electricity at medium voltage based on year 2017

[10] Bareiß et al., 2019, Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems, Applied Energy. Assumptions: LCI is based on future material and energy demand of PEM. Electricity supply via Revolution Scenario for 2050.

[11] Deutz et al., 2021, Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption, Nature Energy. Assumptions: future scenario with "Global 2050" as energy supply scenario and heat from a heat pump

[12] EWI - Energy Research & Scenarios gGmbh, 2018, The energy market in 2030 and 2050 – The contribution of gas and heat infrastructure to efficient carbon emission reductions

[13] https://www.ews-consulting.com/tl_files/media/ews_global/downloads/pdf%20Sonstiges/studie_akzeptanz_wp_muf_frisch_sokic_2018.pdf, accessed 23.09.2021

factors to impact the social acceptance so far are expected to be more towards infrastructural and technological topics than on a designated CO_2-based product of this CCU study. Most of the discussed CCU options in this study are not final goods, but are used as intermediates. Ultimately, the discussion is about whether CO_2 will be accepted as a sustainable raw material in future.

- The analytic hierarchy process (AHP), which was developed by Saaty[14] was used for weighting the criteria. It is based on the pair-wise comparison of each criteria inside a group which leads in the end to a hierarchy. The main driver for the obtained weighting was that the considered processes should be more sustainable than the existing conventional processes. Thus, the highest weighting of 46% was obtained for the criteria “Environmental Compatibility”, with the carbon footprint in the future being most decisive. The economic and technical aspects were seen as equally important, achieving ratings of 17% and 16%. In the technical criteria, the TRL was considered as the critical parameter (83%). For the economic feasibility, the economic viability was found as the most important variable (51%) followed by the CO_2 avoidance cost (26%). For the rollout, the market growth, rollout potential and employment effect were valued at a similar level (23–30%).
- An initial list of CCU options was gathered by literature research and brainstorming. After filtering by selected requirements, the remaining CCU ideas were divided into three categories: chemicals (34), fuels (7) and proteins (6). In case of chemicals, multiple CO_2-based pathways were considered if applicable. Overall, eighteen different chemicals have been assessed.
- Industry experts expect that methanol will be implemented as a platform chemical and it might be the energy carrier of the future.[15] A strong benefit of methanol is, that it can be easily produced from renewable sources and thus, if treated and used in a suitable way, can be environmentally friendly. Furthermore, methanol delivers one significant advantage: as a liquid, it is easy to handle and has a higher energy density than gaseous fuels. Storing, transportation and distribution is much more practical than for gas or electricity. Besides the actual methanol production, there are several pathways to convert methanol to desired products. For this study, two exemplary pathways were chosen and evaluated on a deeper level.
- If syngas is produced by utilizing CO_2 it would have a significant impact to improve the carbon footprint of several syngas-based processes. As a consequence, three syngas production options were evaluated in depth. Additionally, one syngas-based pathway was reviewed further. It has to be kept in mind that syngas can only be transported over short distances and further processing typically occurs nearby.
- The selected CCU ideas in the three areas – chemicals, fuels and proteins – were prioritized based on the criteria matrix and respective weighting. A sensitivity analysis based on the theoretical energy demand and a more realistic energy demand of the CCU options showed,

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[14] Brunelli, 2014, Introduction to the analytic hierarchy process, Springer

[15] IRENA and Methanol Institute, 2021, Innovation Outlook: Renewable Methanol, International Renewable Energy Agency.

that the overall scoring did not change significantly, with the exception of ethylene, which dropped from position 7 down to 29.

- CO_2-based chemicals: due to the variety of assessed chemicals, additional focus was put towards CO_2 reduction potential within NRW (> 30 kt/a) and a positive economic viability. However, a positive economic viability according to the definition in section 5.1 does not mean that there is a positive business case of the respective process. It is rather a first assessment to estimate if the costs for required raw materials and energy demand would be covered by the market price. Options with a negative economic viability have a significantly lower probability to achieve a positive business case and were not considered further. The resulting prioritization list for chemicals shows 16 CCU options for eight different chemicals, as some chemicals could be realized with different CO_2-based pathways. Some of them, would combine fossil resources (like ethylene and natural gas) and CO_2 as a second resource. As top candidates, acrylic acid, formic acid, ethanol and acetic acid were identified.
- CO_2-based fuels: Fischer-Tropsch-based kerosene scored best within the selected fuel options, mainly because of the strength in environmental compatibility, technical readiness and market demand.
- CO_2-based proteins / biomass: general produce, protein rich biomass and single cell proteins and nutraceuticals have been assessed in a high-level comparison. They represent a wide variety of options, which require CO_2 for growth. The general produce option (tomatoes) scored best, followed by Lemna (protein-rich biomass) and microbial proteins. The evaluation helps to identify the strength of each option as a basis for decision making. It is necessary to consider arguments like local production of biomass, sustainability factors like water and land use and the possibility to use waste heat to satisfy the rather high heat demand for greenhouse operations. Often, the trade-off for less land and water consumption is a higher energy demand. With increasing availability of renewable energy, enough energy could be provided to feed the growing population with these investigated alternative protein sources. The aim of this study in regards to the biomass/protein topic is to create a broader awareness of the solution space and to initiate discussions or even projects picking up these topics.

Part C: Concepts for a Site in NRW

- The aim of the discussed concepts is not to present a detailed engineered case but to describe options, which could be deepened further with relevant stakeholders along the overall value chain. In general, there are different possibilities for any specific site: one is the focus on local demand of a given chemical (site demand or case 1), while another one is the assessment of the available CO_2 source for conversion into a selected chemical (site CO_2 or case 2). The latter case needs to consider the overall demand of the respective chemical in NRW or Germany in order to stay within realistic market opportunities.
- The chemical park in Hürth-Knapsack (close to Cologne) was selected as an exemplary site for a concept development. Discussions with the site operator YNCORIS GmbH & Co. KG resulted in the selection of formic acid and acetic acid, together with its feedstock methanol, as promising candidates for CO_2-based chemicals of interest. Furthermore, a waste to energy plant operated by eew Energy Saarbrücken is located in Knapsack, with about 300 kt/a CO_2

emissions, which was considered as local CO_2 point source for the concept. A comparison of the different options was based on technological, economical and local aspects.

Technological Review:

- One major difference is the TRL: acetic acid can be produced by a state-of-the-art facility, requiring CO_2-based methanol and/or carbon monoxide to become CO_2-based acetic acid. The TRL of CO_2-based methanol production is rather high, and demo-scale projects could be easily deployed on-site. CO_2-based carbon monoxide is also at demo scale (TRL 8)[132], but targeting smaller production units than potentially required for acetic acid production. Both formic acid options, i.e., electrochemical route and via CO_2 hydrogenation, are still on lower TRL and the next step would be a pilot scale facility to develop the technologies further.
- The best fit depends crucially on the intended timeline and envisioned scale of CCU application on the Knapsack site. Formic acid allows for smaller pilot projects, which might be eligible for public funding. Additionally, upcoming changes in regulation or incentive schemes might become clearer by the time these technologies reach commercial potential. On the other hand, the acetic acid case would start with a conventional full-scale plant, and depending on economic or other motivation, the feedstock can gradually be replaced by CO_2-based feedstocks or other sustainable feedstock options. The flexibility in feedstock (conventional, CO_2-based or other sustainable sources) has the benefit to react more variable on changes in the market, regulations or other impacting factors.

Economic Review:

- Net present value (NPV) calculation was used to assess the economic viability from an investor's point of view. As the economic assessment undertaken in this study is based on rather general information, three scenarios were used for NPV calculations: a base scenario considering the current price and cost estimates as outlined in part B of this study and additionally a pessimistic, and optimistic scenario to reflect on potential market fluctuations.
- The production volume of the plants was categorized in two cases: site demand and site CO_2. For the site demand case, the production volume is equal to the demand within the chemical park and the site CO_2 case has a production volume, which utilizes the entire CO_2 available from the waste to energy plant.
- For formic acid (hydrogenation) all NPVs were negative, and for acetic acid and methanol all NPVs besides the optimistic scenario (site CO_2) were negative. The NPVs of formic acid (electrochemical) were positive for the optimistic scenarios (site demand & site CO_2) and the base scenario (site CO_2). Since a conventional process was considered for acetic acid production, which is feasible from a global perspective, it has to be assumed that either the used cost assumptions are too conservative, since economic feasibility (NPV >0) is only achieved in the optimistic case or that acetic acid production requires locations with respective lower cost structure.
- Avoiding the use of fossil carbon and transforming towards a sustainable, CO_2-based feedstock production is the main focus of this study. Hence, a sensitivity analysis of the economic assessment of the large-scale options (site CO_2) was conducted to identify the main cost drivers.

  - Main cost driver for (conventional) acetic acid production is the CAPEX, followed by market price and cost for feedstock and energy. In case of CO_2-based feedstock, higher market price and/or reduced CAPEX would be required to account for the higher feedstock costs.
  - CO_2-based methanol cost is mainly driven by cost for renewable hydrogen.
  - Cost for formic acid production via hydrogenation of CO_2 is mainly driven by the market price and catalyst cost.
  - Cost for formic acid production via the electrochemical pathway is mainly driven by the market price and electricity costs.
- In view of climate change, the need to avoid CO_2 emissions is obvious and often the main question is the cost for CO_2 avoidance. There are different approaches possible to calculate these costs. Here, the results of the NPV calculations were used and combined with the identified carbon footprint reduction potential of the respective chemical compared to the conventional process (future scenario). For the different scenarios discussed within this study for CO_2-based acetic acid, the CO_2 avoidance cost ranges from 144 EUR to 249 EUR per ton CO_2. For formic acid, the CO_2 avoidance cost in the base case scenario for the larger plant is 89 EUR/tCO_2 for the hydrogenation pathway, while the electrochemical pathway had a neutral/minimal positive NPV. The cost for CO_2 capture was included in the NPV calculations.

Local Aspects:

- At Knapsack chemical park, there is about 16 ha of expansion area foreseen, which is more than sufficient space for the described CCU concepts, even including the required electrolyzer units. The space demand for the different options ranges from 0.12 ha to 1.5 ha.
- For new plants, the exact location of available space is less critical. However, a carbon capture plant should be located close to the CO_2 point source. Based on the anticipated CO_2 capture capacity of about 290 kt/a, a footprint of approximately 25 m x 60 m can be assumed as a first estimate[137,16]. A bird's eye view shows, that some free space is available in close proximity to the waste-to-energy plant and that retrofitting a carbon capture plant might be feasible.
- The required heat demand for a carbon capture plant is in line with other facilities located within the chemical site at Knapsack. Potential electrical power demand of 3 MW for CO_2 compression and liquefaction, if required, can very likely be provided as well.
- The different CCU options, require however significant amount of additional electricity, either for hydrogen production needed for methanol or formic acid production, or for the electrochemical formic acid process. While the plain acetic acid plant has a rather low electricity demand and a moderate demand for heat, the corresponding methanol synthesis would require about 40 to 50 MW electrical power (in case of site CO_2 supply case). The formic acid application would require even more power. This amount of additional electrical capacity can not be sourced from within the chemical park and would require system expansion and alignment with respective providers. Due to the required network expansion

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[16] https://akercarboncapture.com/offerings/just-catch/, accessed 23.09.2021

work, the overall cost for such a project would increase. An alternative for the high electrical energy demand in case of methanol production and formic acid production via hydrogenation could be the supply of hydrogen via a pipeline network. It might be a more strategic decision of the site developer if in future access to a hydrogen pipeline is more beneficial than network expansion to deal with the electrification needs within the chemical industry.

Conclusion and Outlook:

- From a regulatory perspective, no incentive is yet in place to support CO_2-based chemicals as CCU options are not eligible carbon reduction measures under the ETS scheme. This might change in the future, but cannot be foreseen. Other subsidies supporting capital investments in such technologies could contribute partially to achieve economic viability, but additional relief for example on energy surcharges to reduce operational costs would still be required.
- In view of climate change, the described way of producing chemicals would contribute to reduce GHG emissions. Based on the future scenario established in the study, CO_2-based acetic acid would have a CO_2 reduction potential between 0.4 to 1.4 kg CO_2 avoided per kg acetic acid when comparing to conventional acetic acid production. The range reflects that either only CO_2-based methanol would be used (0.4 kg CO_2 avoided / kg acetic acid) or CO_2-based methanol and CO_2-based carbon monoxide would be used (1.4 kg CO_2 avoided / kg acetic acid). The formic acid options would avoid about 1.7 to 1.8 kg CO_2 per kg formic acid compared to the conventional process. Considering the CO_2 avoided per product, formic acid has a larger impact than acetic acid. However, depending on the market demand, the total amounts produced differ significantly as the anticipated German market for acetic acid is more than double the volume of formic acid (about 700 kt/a versus 300 kt/a). The impact on GHG emissions savings for the chemical site assessed in the concept phase has even a broader variation, depending if either the local chemical demand is to be met or if the CO_2 emission from the local waste to energy plant is converted.
- Several projects for CO_2-utilization are ongoing within NRW, like Covestro's CO_2-based polyols and Evonik's CO_2-based butanol and hexanol. The assessment undertaken within this study could show, that there is potential for additional CO_2-based products within NRW. The potential future reduction of greenhouse gases accumulates to about 1.2 Mt CO_2/a, based on estimated NRW demand, just for the top 15 chemicals assessed within this study. The scope 3 emissions of NRW-based chemical industry is estimated to be 19 Mt CO_2/a.[17] From a turnover perspective, these selected chemicals account only for 900 Mio EUR of the overall 42,300 Mio EUR turnover of NRW based chemical industry.[18]
- The reduction potential of CO_2-eq emissions for CO_2-based kerosene is around 4.8 Mt CO_2/a, but this requires about 67.5 TWh/a renewable energy for hydrogen production to cover the kerosene demand of NRW. Respective infrastructure expansion of the electrical grid and /

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[17] Based on the roadmap 2050 of VCI, assuming 30% of German scope 3 emissions to be representative for NRW

[18] https://www.wirtschaft.nrw/chemie and own calculation for selected chemicals, accessed 23.09.2021

or hydrogen pipeline to relevant sites is essential for successful implementation of CCU technologies within NRW.

- The total energy demand differs between CO_2-based chemicals and CO_2-based fuels due to the different reduction equivalent needed. Based on the chemicals and fuels assessed within this study, the average energy demand per avoided CO_2 can be calculated to 10.2 MWh/t $CO_{2,\ \text{avoided}}$ for chemicals and 14.1 MWh/t $CO_{2,\ \text{avoided}}$ for fuels. The energy demand includes electricity, heat and hydrogen demand. The avoided CO_2 is based on the carbon footprint reduction potential determined for the future scenario.

2 Zusammenfassung

Hintergrund

Nordrhein-Westfalen (NRW) ist die industrielle Kernregion Deutschlands und erwirtschaftet das höchste Bruttoinlandsprodukt der Bundesländer. Zu dem bereits in der Vergangenheit eingeleiteten Strukturwandel mit der Schließung der Tiefbaugebiete für Steinkohleabbau bis Ende 2018 kommt nun der Strukturwandel durch den geplanten Kohleausstieg im Braunkohlerevier zwischen Aachen, Düsseldorf und Bonn hinzu. Dies ist auf der einen Seite eine Herausforderung, auf der anderen Seite aber auch eine Chance, neue Technologien zu entwickeln und in diese zu investieren, um damit die Industrieregion nicht nur wirtschaftlich, sondern auch hinsichtlich der Arbeitsplätze unterstützen zu können.

In dieser Studie wird das Potenzial der CO_2-Nutzung über sogenanntes „Carbon Capture and Utilization“ (CCU) nicht nur im Hinblick auf die Wiederverwertung von Kohlenstoff und die Verringerung der Treibhausgasemissionen bewertet, sondern auch im Hinblick auf die Erhaltung der lokalen Industrie und den Aufbau neuer lokaler Industrien auf der Grundlage nachhaltiger Technologien. Viele Rohstoffe, welche auf Kohlenstoff basieren, sind derzeit fossilen Ursprungs oder stehen vor anderen Nachhaltigkeitsproblemen. Daher liegt der Schwerpunkt dieser Studie auf der Ermittlung des Potenzials von CO_2-basierten Chemikalien, Kraftstoffen und alternativen Proteinquellen.

Der Bericht gliedert sich in drei Teile A, B und C. Der erste Teil A bewertet die Infrastruktur in NRW, gefolgt von Teil B, der die potenziellen CCU-Optionen in der Region analysiert und eine Rangliste erstellt. Teil C führt eine detaillierte Fallstudie der vielversprechendsten Ideen einschließlich einer wirtschaftlichen Bewertung durch. Die wichtigsten Ergebnisse der einzelnen Teile werden im Folgenden zusammengefasst.

Ergebnisse

Teil A: Bewertung der NRW-Infrastruktur

- NRW ist die industrielle Kernregion Deutschlands und erwirtschaftet das höchste Bruttoinlandsprodukt der Bundesländer. Rund 20 % der Erwerbstätigen sind in der Industrie beschäftigt, die ca. 27 % der Bruttowertschöpfung erwirtschaftet. Der landwirtschaftliche Sektor trägt mit ca. 17 % zur Bruttowertschöpfung bei.
- Der Schwerpunkt der Studie liegt auf dem Rheinischen Revier, welches sich im südwestlichen Rheinland befindet. Es ist derzeit eine Kernregion für den Braunkohleabbau und dazugehörige Kraftwerke.
- Die installierte elektrische Leistung in NRW beträgt ca. 41 GW, was auf den Energieträgern Braunkohle (10,7 GW), Erdgas (8,4 GW), Steinkohle (6,5 GW), Windkraft (5,8 GW) und Solarenergie (5,2 GW) basiert. Im Rheinischen Revier dominieren die Braunkohlekraftwerke, während in den übrigen Teilen von NRW Gas- und Steinkohlekraftwerke stehen.[1] Die Nettostromnachfrage wird zu 51 % von der Industrie, zu 27 % von den Haushalten, zu 20 % von den Unternehmen und zu 1,6 % vom Verkehrssektor verursacht.[2]

- In ganz NRW gibt es 13 Chemieparks, die hauptsächlich in der Nähe des Rheins oder im nördlichen Ruhrgebiet liegen. Weitere Chemieanlagen befinden sich außerhalb der Chemieparks.
- In NRW gibt es zwei Raffineriestandorte: Shell im Raum Köln und BP im Raum Gelsenkirchen. Sie sind zwei der drei größten Raffineriestandorte in Deutschland mit einer Verarbeitungskapazität von zusammen 30 Mio. t/a Rohöl und rund 4.900 Beschäftigten. Ihre Pipelinenetze sind mit Rotterdam, Wilhelmshaven/Hamburg und dem Raum Frankfurt/Ludwigshafen verbunden.
- In NRW werden ca. 16 Mio. t/a Rohstahl produziert (38 % der gesamten Stahlproduktion in Deutschland) was zu einer derzeitigen Beschäftigungszahl von rund 45.000 Menschen in der Stahlindustrie führt, da fast die Hälfte der deutschen Stahl- und Metallverarbeitungsunternehmen in NRW produziert.[3] Außerdem tragen die in NRW ansässigen Unternehmen rund ein Viertel zum deutschen Umsatz in der Nichteisenmetallerzeugung und -verarbeitung bei. Duisburg ist sogar der größte Stahlstandort in Europa.
- Der größte Teil der Güter wird über die Straße transportiert, was 79 % des transportierten Gewichts in Deutschland im Jahr 2018 ausmacht. Neben dem Straßenverkehr sind in Deutschland der Transport über die Schiene (8,5 % des transportierten Gewichts im Jahr 2018), die Binnenschifffahrt (4,2 % des transportierten Gewichts im Jahr 2018) und der Seeverkehr (6,3 % des transportierten Gewichts im Jahr 2018) sowie in geringerem Umfang die Luftfracht (0,1 % des transportierten Gewichts im Jahr 2018) von Bedeutung.[4]
- Es existiert ein europaweites Leitungsnetz für Erdgas mit einem dichten Netz im Rheinischen Revier und im Ruhrgebiet. Die Gasfernleitungsbetreiber schlagen im "Netzentwicklungsplan Gas" auf der Grundlage von zwei Gasnachfrageszenarien für Deutschland den zukünftigen Ausbau der Netzkapazitäten für die Jahre 2020 bis 2030 vor.
- Derzeit betreibt Air Liquide das längste Wasserstoff-Pipelinenetz Deutschlands, welches im Chemiepark Marl beginnt und mit einer Länge von 240 km über Bottrop, Duisburg und Düsseldorf nach Castrop-Rauxel und nach Leverkusen führt. Eine 5.900 km lange Pipeline zwischen Lingen und Gelsenkirchen ist von der Initiative GET H2 geplant. Bei dieser Leitung handelt es sich derzeit um eine von Nowega und OGE betriebene Erdgasleitung, die bis 2023 auf eine H_2-Pipeline umgestellt werden soll, um NRW mit grünem Wasserstoff zu versorgen.
- Fast die Hälfte von NRW wird als landwirtschaftliche Fläche genutzt (1,45 Millionen ha). Diese landwirtschaftliche Fläche besteht zu 72 % aus Ackerland, zu 27 % aus Weideland und nur zu 1 % aus Dauerkulturen. Die Viehzucht spielt in NRW eine große Rolle, wobei Geflügel und Schweine die wichtigsten Nutztiere sind. Jährlich werden in NRW fast 4 Millionen Tonnen Futtermittel produziert, was sich aus heimischen und importierten Komponenten zusammensetzen. Das Land NRW ist der zweitgrößte Futtermittelproduzent in Deutschland mit über 40.000 beteiligten Unternehmen.

Teil B: CCU-Ideen-Ranking

- Die Kriterien für den Vergleich der verschiedenen CCU Verfahren wurden in fünf Gruppen unterteilt, die folgende Aspekte umfasst: Technik, Infrastruktur, Umweltverträglichkeit, wirtschaftliche Machbarkeit und Rollout-Szenario. Innerhalb dieser Gruppen wurden Unterkriterien für eine weitere Aufschlüsselung verwendet, so dass insgesamt 21 Unterkriterien zur Verfügung standen. Der entsprechende Bewertungsleitfaden ist in Abschnitt 5.1 dargelegt.
- Es wurden Lebenszyklusanalysen (LCA) der CCU-Prozesse und der jeweiligen konventionellen Produktion durchgeführt, um durch deren Vergleich das Reduktionspotenzial an CO_2-Equivalenten für jeden CCU-Prozess zu ermitteln.
- Die Bewertung der Kategorie Umweltverträglichkeit der CCU-Ideen nutzt zwei Szenarien, welche die Auswirkung unterschiedlicher Bezugsquellen an CO_2, H_2, Strom und Wärme auf die Treibhausgasemissionen und die Toxizität sowohl für den CCU Pfad als auch für den konventionellen Prozess darstellen. Das "current"-Szenario beschreibt die Produktion mit Randbedingungen, die dem heutigen Stand der Technik entsprechen, d.h. H_2 über Methandampfreformierung[7], CO_2-Abscheidung mit Aminwäsche aus Zementwerksabgasen[8], deutscher Strommix[9] und Wärmebereitstellung durch einen Marktmix aus Erdgas, Öl, Kohle und Biogas. Im Gegensatz dazu nimmt das Szenario "green future" Randbedingungen an, die geringere Treibhausgasemissionen versprechen: H_2 aus PEM-Elektrolyse[10], CO_2 durch direkte Luftabscheidung[11], ein Strommix gemäß dem "Revolution Szenario" einer Studie von EWI für 2050[12] und Wärmeversorgung durch Strom. Der angenommene Strommix setzt sich aus Windkraft (59 %) und Photovoltaik (22 %), aber auch aus Gas (10 %) zusammen. In dieser Studie wird davon ausgegangen, dass die elektrische Energie über das Netz eingespeist wird, um Auswirkungen der Intermittenz oder anderer begrenzenden Faktoren der erneuerbaren Energiequellen zu vermeiden.
- Die gesellschaftliche und öffentliche Akzeptanz neuer Technologien ist entscheidend für deren erfolgreiche Einführung. Mehrere Themen haben in der Vergangenheit gezeigt, wie der Mangel an öffentlicher Beteiligung und sozialer Akzeptanz die Einführung neuer Technologien verzögert oder sogar verhindert hat. Ein bekanntes Beispiel hierfür ist das Problem der Windkraftanlagen, deren Errichtung öfters durch Bürgerinitiativen behindert werden („not in my backyard“ Problem), wobei erneuerbare Energien an sich eine hohe Akzeptanz erfahren.[13] Die wichtigsten Faktoren, die sich bisher auf die gesellschaftliche Akzeptanz ausgewirkt haben, dürften eher infrastrukturelle und technologische Themen sein und weniger ein bestimmtes CO_2-basiertes Produkt dieser CCU-Studie betreffen. Insbesondere da die meisten der in dieser Studie diskutierten CCU-Optionen keine Endprodukte sind, sondern als Zwischenprodukte verwendet werden. Letztlich geht es um die Frage, ob CO_2 in Zukunft als nachhaltiger Rohstoff akzeptiert werden wird.
- Zur Gewichtung der Kriterien wurde der von Saaty[14] entwickelte analytische Hierarchieprozess (AHP) verwendet. Er basiert auf dem paarweisen Vergleich jedes Kriteriums innerhalb einer Gruppe, was schließlich zu einer Hierarchie führt. Ein Hauptaspekt in der Studie ist, dass die betrachteten Prozesse nachhaltiger sein sollten als die bestehenden konventionellen Prozesse. Daher wurde die höchste Gewichtung von 46 %

dem Kriterium "Umweltverträglichkeit" zugeschrieben, wobei der zukünftige CO_2-Fußabdruck am entscheidendsten war. Die wirtschaftlichen und technischen Aspekte wurden mit 17 % bzw. 16 % als gleich wichtig eingestuft. Bei den technischen Kriterien wurde die Technologiereife (TRL) als der entscheidende Parameter angesehen (83 %). Bei der wirtschaftlichen Durchführbarkeit wurde die Wirtschaftlichkeit als wichtigste Variable angesehen (51 %), gefolgt von den CO_2-Vermeidungskosten (26 %). Bei dem Kriterium Roll-Out wurden das Marktwachstum, das Einführungspotenzial und der Effekt auf Beschäftigungszahlen auf ähnlichem Niveau bewertet (23-30 %).

- Eine erste Liste von CCU-Optionen wurde durch Literaturrecherche und interne Diskussionen zusammengestellt. Nach einer Vorauswahl wurden die verbleibenden CCU-Ideen in drei Kategorien unterteilt: Chemikalien (34), Kraftstoffe (7) und Proteine (6). Bei den Chemikalien wurden teilweise mehrere CO_2-basierte Wege berücksichtigt. Insgesamt wurden achtzehn verschiedene Chemikalien bewertet.
- Branchenexperten gehen davon aus, dass Methanol in Zukunft als Plattformchemikalie eingesetzt wird und somit der Energieträger der Zukunft sein könnte[15]. Ein großer Vorteil von Methanol ist dessen verhältnismäßig einfache Herstellung unter Nutzung erneuerbarer Energien oder Rohstoffen. Darüber hinaus bietet Methanol einen entscheidenden Vorteil: Als Flüssigkeit hat es eine höhere Energiedichte als gasförmige Energieträger und es ist auch einfacher zu handhaben. Die Lagerung, der Transport und die Verteilung sind damit wesentlich praktikabler als bei Gas oder Strom. Aus der Plattformchemikalie Methanol können die verschiedensten Produkte hergestellt werden. Diese Studie begrenzt sich daher auf zwei exemplarische Weiterverarbeitungsschritte von Methanol.
- Wenn Synthesegas aus CO_2 anstelle von fossilem Kohlenstoff hergestellt wird, hätte dies eine erhebliche Verbesserung des CO_2-Fußabdrucks vieler synthesegasbasierter Prozesse zur Folge. Daher wurden drei Optionen für die Erzeugung von Synthesegas eingehender bewertet. Zusätzlich wurde ein auf Synthesegas basierender Weiterverarbeitungsschritt näher untersucht. Dabei ist zu berücksichtigen, dass Synthesegas nur über kurze Entfernungen transportiert werden kann und die Weiterverarbeitung in der Regel in der Nähe stattfindet.
- Die ausgewählten CCU-Ideen in den drei Bereichen Kraftstoffe, Chemikalien und Proteine wurden auf der Grundlage der Kriterienmatrix und der jeweiligen Gewichtung nach Prioritäten geordnet. Eine Sensitivitätsanalyse auf der Grundlage des theoretischen Energiebedarfs und eines realistischeren Energiebedarfs der CCU-Optionen ergab, dass sich die Gesamtbewertung nicht wesentlich verändert hat, mit Ausnahme von Ethylen, das von Platz 7 auf Platz 29 zurückfiel.
- CO_2-basierte Chemikalien: Aufgrund der Vielfalt der bewerteten Chemikalien wurde eine weitere Eingrenzung vorgenommen, indem das mögliche CO_2-Reduktionspotenzial innerhalb von NRW (> 30 kt/a) und die Wirtschaftlichkeit (positiv) eingeschränkt wurde. Eine positive Wirtschaftlichkeit (siehe Definition in Abschnitt 5.1) bedeutet jedoch nicht zwingend, dass ein positiver Business Case der jeweiligen CCU-Option vorliegt. Es handelt sich vielmehr um eine erste Einschätzung, ob die Kosten für die benötigten Rohstoffe und den Energiebedarf durch den Marktpreis des Produktes gedeckt werden können. CCU-

Optionen mit einer negativen Wirtschaftlichkeit haben eine deutlich geringere Wahrscheinlichkeit, einen positiven Business Case zu erreichen und wurden daher ausgeschlossen. Die sich daraus ergebende Prioritätenliste für Chemikalien enthält 16 CCU-Optionen für acht verschiedene Chemikalien, da einige Chemikalien auf verschiedenen CO_2-basierten Pfaden hergestellt werden könnten. Einige von ihnen kombinieren fossile Ressourcen (wie Ethylen und Erdgas) und CO_2 als Kohlenstoffquelle. Als vielversprechende CCU-Optionen wurden Acrylsäure, Ameisensäure, Ethanol und Essigsäure ermittelt.

- CO_2-basierte Kraftstoffe: Kerosin auf Fischer-Tropsch-Basis schnitt unter den ausgewählten Kraftstoffoptionen am besten ab, vor allem wegen der guten Umweltverträglichkeit, des Technologiereifegrads und der Marktnachfrage.
- CO_2-basierte Proteine/Biomasse: Landwirtschaftliche Produkte, proteinreiche Biomasse bis hin zu einzelligen Proteinen und Nahrungsergänzungsmitteln wurden in einem Vergleich bewertet. Dadurch wird eine breite Palette von Optionen, die CO_2 für das Wachstum benötigen, abgebildet. Das landwirtschaftliche Produkt (Tomaten) schnitt am besten ab, gefolgt von Lemna (proteinreiche Biomasse) und mikrobiellen Proteinen. Die Bewertung soll dabei helfen, die Stärken der einzelnen Optionen aufzuzeigen und somit als Entscheidungsgrundlage dienen. Aspekte wie die lokale Erzeugung von Biomasse, Nachhaltigkeitsfaktoren wie Wasser- und Bodennutzung und die Möglichkeit der Nutzung von Abwärme zur Deckung des recht hohen Wärmebedarfs für den Gewächshausbetrieb sollten dabei berücksichtigt werden. So folgt aus einem geringeren Flächen- und Wasserverbrauch oft ein erhöhter Energiebedarf. Mit der zunehmenden Verfügbarkeit von erneuerbaren Energien könnte der Energiebedarf solcher Erzeugungsmethoden gedeckt werden, um die wachsende Bevölkerung zu ernähren. Das Ziel dieser Studie im Bereich Biomasse/Protein ist es, ein breiteres Bewusstsein für mögliche Lösungen zu schaffen und damit Diskussionen anzuregen oder sogar Projekte zu initiieren.

Teil C: Konzepte für den Standort NRW

- Ziel der in Teil C diskutierten Konzepte ist es nicht, einen Prozess im Detail technisch zu konstruieren, sondern Optionen zu beschreiben, die zusammen mit Interessengruppen der gesamten Wertschöpfungskette weiter vertieft werden könnten. Für die Ausarbeitung der Prozesse können verschiedene standortspezifische Rahmenbedingungen herangezogen werden. Eine Möglichkeit besteht darin auf den lokale Bedarf der adressierten Chemikalie („site demand“ oder „Case 1“) einzugehen, während die andere auf der kompletten Nutzung einer lokalen CO_2-Quelle für die Umwandlung in eine ausgewählte Chemikalie beruht („site CO_2“ oder „Case 2“). Im letzteren Fall muss die Gesamtnachfrage nach der betreffenden Chemikalie in NRW oder Deutschland berücksichtigt werden, um realistische Marktchancen zu berücksichtigen.
- Der Chemiepark in Knapsack wurde als exemplarischer Standort für eine Konzeptentwicklung ausgewählt. In Gesprächen mit dem Standortbetreiber YNCORIS GmbH & Co. KG wurden Ameisensäure und Essigsäure, inklusive dem Rohstoff Methanol, als potenziell interessante CO_2-basierte Chemikalien ausgewählt. Darüber hinaus existiert in Knapsack eine von eew Energy Saarbrücken GmbH betriebene Müllverbrennungsanlage mit einem jährlichen CO_2-Ausstoß von ca. 300 kt/a, die als lokale CO_2-Punktquelle für das

Konzept in Betracht gezogen wurde. Ein Vergleich der verschiedenen Optionen erfolgte nach technologischen, wirtschaftlichen und lokalen Gesichtspunkten.

Technologische Betrachtung:

- Ein wesentlicher Unterschied der betrachteten CCU-Optionen ist deren technologischer Reifegrad (TRL). Essigsäure könnte mit einer konventionellen Anlage hergestellt werden, die CO_2-basiertes Methanol und/oder Kohlenmonoxid verarbeiten kann, sodass CO_2-basierte Essigsäure hergestellt wird. Der TRL der CO_2-basierten Methanolproduktion ist recht hoch, und Projekte im Demo-Maßstab könnten leicht vor Ort umgesetzt werden. CO_2-basiertes Kohlenmonoxid befindet sich ebenfalls im Demo-Maßstab (TRL 8)[132], bedient aber bisher nur kleinere Produktionseinheiten als sie für die Essigsäureproduktion benötigt werden würden. Beide Ameisensäureoptionen, d. h. die elektrochemische Route und die CO_2-Hydrierung, befinden sich noch im unteren TRL-Bereich, und der nächste Schritt wäre der Bau einer Pilotanlage, um die Technologien weiter zu entwickeln.
- Was am besten geeignet ist, hängt vor allem vom Zeitplan und dem gewünschten Umfang der CCU-Anwendung auf dem Gelände von Knapsack ab. Ameisensäure ermöglicht kleinere Pilotprojekte, die für eine öffentliche Finanzierung in Frage kommen könnten. Darüber hinaus könnten Pläne zur potentiellen Anpassung der Regulationsmechanismen wie z.B. die Einbindung von Anreizsysteme konkret werden, bis diese Technologien ihre Marktreife erlangen. Im Falle der Essigsäure würde man hingegen mit einer konventionellen Anlage im großen Maßstab beginnen, und je nach wirtschaftlicher oder anderweitiger Motivation können die Rohstoffe schrittweise durch CO_2-basierte Rohstoffe oder andere nachhaltige Rohstoffoptionen ersetzt werden. Die Flexibilität bei den Rohstoffen (konventionelle, CO_2-basierte oder andere nachhaltige Quellen) hat den Vorteil, dass man variabler auf Änderungen des Marktes, der Vorschriften oder anderer Einflussfaktoren reagieren kann.

Wirtschaftliche Betrachtung:

- Die Berechnung des Kapitalwerts (Net Present Value, NPV) wurde verwendet, um die Wirtschaftlichkeit aus der Sicht der Investoren zu bewerten. Da die in dieser Studie vorgenommene wirtschaftliche Bewertung auf eher allgemeinen Informationen beruht, wurden für die Kapitalwertberechnungen drei Szenarien verwendet: ein Basisszenario unter Berücksichtigung der aktuellen Preis- und Kostenschätzungen, die Teil B dieser Studie zu Grunde liegen, sowie ein pessimistisches und ein optimistisches Szenario, um mögliche Marktschwankungen zu berücksichtigen.
- Das Produktionsvolumen der Anlagen wurde in zwei Fälle eingeteilt: Standortbedarf („site demand“) und Standort-CO_2 („site CO_2). Im Fall des Standortbedarfs entspricht das Produktionsvolumen dem Bedarf innerhalb des Chemieparks und im Fall der Standort-CO_2-Produktion wird das gesamte verfügbare CO_2 aus der Müllverbrennungsanlage genutzt.
- Für Ameisensäure, produziert über CO_2-Hydrierung, waren alle NPVs negativ, und für Essigsäure und Methanol waren alle NPVs außer dem optimistischen Szenario (Standort-CO_2) negativ. Dahingegen waren die NPVs für Ameisensäure (elektrochemisch) für die optimistischen Szenarien (Standortbedarf und Standort-CO_2) und für das Basisszenario (Standort-CO_2) positiv. Da für die Essigsäureproduktion ein konventioneller Prozess

betrachtet wurde, der aus globaler Sicht finanziell machbar ist, muss davon ausgegangen werden, dass entweder die verwendeten Kostenannahmen zu konservativ sind, da die Wirtschaftlichkeit (NPV >0) nur im optimistischen Fall erreicht wird, oder dass die Essigsäureproduktion Standorte mit entsprechend niedrigerer Kostenstruktur erfordert.

- Die Vermeidung des Einsatzes von fossilem Kohlenstoff und die Umstellung auf eine umweltverträglichere, CO_2-basierte Rohstoffproduktion ist das Hauptaugenmerk dieser Studie. Daher wurde eine Sensitivitätsanalyse der wirtschaftlichen Bewertung der großtechnischen Optionen (CO_2-Standort) durchgeführt, um die wichtigsten Kostenfaktoren zu ermitteln.
    - Hauptkostentreiber für die (konventionelle) Essigsäureproduktion sind die Investitionsausgaben (CAPEX), gefolgt vom Marktpreis der Essigsäure und den Kosten für benötigte Rohstoffe und Energie. Im Falle von CO_2-basierten Rohstoffen wäre ein höherer Marktpreis und/oder ein geringerer CAPEX erforderlich, um die höheren Kosten für die Rohstoffe auszugleichen.
    - Die Kosten für CO_2-basiertes Methanol werden hauptsächlich durch die Kosten für erneuerbaren Wasserstoff bestimmt.
    - Die Kosten für die Herstellung von Ameisensäure durch Hydrierung von CO_2 werden hauptsächlich durch den Marktpreis der Ameisensäure und die Katalysatorkosten beeinträchtigt.
    - Die Kosten für die elektrochemische Herstellung von Ameisensäure werden hauptsächlich durch den Marktpreis und die Stromkosten beeinflusst.
- Angesichts des Klimawandels liegt die Notwendigkeit, CO_2-Emissionen zu vermeiden, auf der Hand. Dabei steht oft die Frage nach den Kosten für die CO_2-Vermeidung im Vordergrund. Es gibt verschiedene Ansätze, um diese Kosten zu berechnen. In dieser Studie wurden die Ergebnisse der Kapitalwertberechnungen (NPV) verwendet und mit dem ermittelten Potenzial zur Verringerung an Treibhausgasemissionen der jeweiligen Chemikalie im Vergleich zum herkömmlichen Verfahren (im Zukunftsszenario „green future“) kombiniert. Für die verschiedenen Szenarien für CO_2-basierte Essigsäure liegen die CO_2-Vermeidungskosten zwischen 144 € und 249 € pro Tonne CO_2. Bei Ameisensäure betragen die CO_2-Vermeidungskosten im Basisszenario für die größere Anlage 89 €/t CO_2 für den CO_2-Hydrierungspfad, während die elektrochemischen Pfade einen neutralen bzw. minimal positiven NPV aufweist. Die Kosten für die CO_2-Abscheidung wurden in die NPV-Berechnungen einbezogen.

Lokale Aspekte:

- Im Chemiepark Knapsack ist eine Erweiterungsfläche von ca. 16 ha vorgesehen, was für die beschriebenen CCU-Konzepte mehr als ausreichend ist, sogar einschließlich der erforderlichen Elektrolyseure. Der Flächenbedarf für die verschiedenen Optionen reicht von 0,12 ha bis 1,5 ha.
- Die CO_2-Abscheidungsanlage sollte in der Nähe der CO_2-Punktquelle errichtet werden. Ausgehend von der erwarteten CO_2-Abscheidungskapazität von etwa 290 kt/a kann als erste Schätzung von etwa 25 m x 60 m als Grundfläche der Anlage ausgegangen werden.[16]

Satellitenbilder zeigen, dass in unmittelbarer Nähe des Müllheizkraftwerks freier Platz vorhanden ist und die Nachrüstung einer CO_2-Abscheidungsanlage machbar sein könnte.

- Der erforderliche Wärmebedarf für eine Anlage zur CO_2-Abscheidung entspricht dem anderer Anlagen am Chemiestandort Knapsack. Ein potenzieller Strombedarf von 3 MW für die CO_2-Kompression und -Verflüssigung kann, falls erforderlich, höchstwahrscheinlich ebenfalls gedeckt werden.
- Die verschiedenen CCU-Optionen erfordern jedoch erhebliche zusätzliche Strommengen, entweder für die Wasserstofferzeugung, welche für die Methanol- oder Ameisensäureproduktion benötigt wird, oder direkt beim elektrochemischen Ameisensäureverfahren. Während die Essigsäureanlage einen eher geringen Strombedarf und einen mäßigen Wärmebedarf hat, würde die entsprechende Methanolsynthese etwa 40 bis 50 MW elektrische Leistung benötigen (für den Fall „Standort CO_2“). Die elektrochemische Ameisensäureproduktion weist sogar einen noch höheren Leistungsbedarf auf. Diese Menge an zusätzlicher elektrischer Leistung kann nicht innerhalb des Chemieparks bereitgestellt werden und würde einen Netzausbau und eine Abstimmung mit den jeweiligen Betreibern erfordern. Aufgrund des erforderlichen Netzausbaus würden sich die Gesamtkosten für ein solches Projekt erhöhen. Eine Alternative für den hohen Bedarf an elektrischer Energie bei der Methanolproduktion und der Ameisensäureproduktion durch CO_2-Hydrierung könnte die Versorgung mit Wasserstoff über ein Pipelinenetz sein. Es könnte eine strategische Entscheidung des Standortentwicklers sein, ob in Zukunft der Zugang zu einer Wasserstoffpipeline vorteilhafter ist als der Stromnetzausbau, um dem Elektrifizierungsbedarf in der chemischen Industrie zu begegnen.

Schlussfolgerung und Ausblick:

- Aus regulatorischer Sicht gibt es noch keine Anreize zur Förderung von Chemikalien auf CO_2-Basis, da CCU-Optionen im Rahmen des Emissionshandelssystems nicht zu den förderfähigen Maßnahmen zur Kohlenstoffreduzierung zählen. Dies könnte sich in Zukunft ändern, ist aber nicht vorhersehbar. Andere Subventionen zur Unterstützung von Kapitalinvestitionen in solche Technologien könnten teilweise dazu beitragen, eine Wirtschaftlichkeit zu erreichen, aber zusätzliche Entlastungen, z.B. bei Energiezuschlägen, zur Senkung der Betriebskosten, wären weiterhin erforderlich.
- Im Hinblick auf den Klimawandel würden die diskutierten Chemikalien dazu beitragen, die Treibhausgasemissionen zu reduzieren. Basierend auf dem in der Studie ermittelten Zukunftsszenario „green future“ hätte CO_2-basierte Essigsäure ein CO_2-Reduktionspotenzial zwischen 0,4 und 1,4 kg vermiedenes CO_2 pro kg. Die Spanne spiegelt wider, ob entweder nur CO_2-basiertes Methanol verwendet wird (0,4 kg vermiedenes CO_2 / kg Essigsäure) oder CO_2-basiertes Methanol und CO_2-basiertes Kohlenmonoxid (1,4 kg vermiedenes CO_2 / kg Essigsäure). Die CO_2-basierte Ameisensäureproduktion würden im Vergleich zum konventionellen Verfahren etwa 1,7 bis 1,8 kg CO_2 pro kg Ameisensäure vermeiden. Betrachtet man die CO_2-Vermeidung pro Produkt, hat Ameisensäure eine größere Auswirkung als Essigsäure. Die Marktnachfrage unterscheidet sich für die produzierten Gesamtmengen jedoch erheblich, da der geschätzte deutsche Markt für Essigsäure mehr als

doppelt so groß ist wie der für Ameisensäure (etwa 700 kt/a gegenüber 300 kt/a). Die Auswirkungen auf die Einsparung von THG-Emissionen für den in der Konzeptphase bewerteten Chemiestandort variieren sogar noch stärker, je nachdem, ob der lokale Bedarf an Chemikalien gedeckt wird oder ob die CO_2-Emissionen aus der lokalen Abfallverbrennungsanlage umgewandelt werden.

- In NRW laufen mehrere Projekte zur CO_2-Nutzung, wie die CO_2-basierten Polyole von Covestro und die CO_2-basierte Butanol- und Hexanol Produktion von Evonik. Die im Rahmen dieser Studie durchgeführte Bewertung konnte zeigen, dass es in NRW ein Potenzial für weitere CO_2-basierte Produkte gibt. Die potenzielle Reduzierung an Treibhausgasen beläuft sich auf etwa 1,2 Mt CO_2/a, basierend auf der abgeschätzten Nachfrage in NRW, allein für die vielversprechendsten 15 Chemikalien in dieser Studie. Im Vergleich, die Scope-3-Emissionen der chemischen Industrie in NRW werden auf 19 Mt CO_2/a geschätzt.[17] Aus der Umsatzperspektive betrachtet, machen diese ausgewählten Chemikalien allerdings nur 900 Mio. € von 42.300 Mio. € Gesamtumsatz der chemischen Industrie in NRW aus.[18]
- Das CO_2-Reduktionspotenzial für CO_2-basiertes Kerosin liegt bei etwa 4,8 Mio. t CO_2/a, erfordert aber etwa 67,5 TWh/a erneuerbare Energie für die Wasserstoffproduktion zur Deckung des Kerosinbedarfs in NRW. Ein entsprechender Ausbau der Netzinfrastruktur und/oder von Wasserstoffpipelines zu den relevanten Standorten ist für eine erfolgreiche Umsetzung der CCU-Technologien in NRW unerlässlich.
- Der Gesamtenergiebedarf unterscheidet sich zwischen CO_2-basierten Chemikalien und CO_2-basierten Kraftstoffen aufgrund der unterschiedlichen erforderlichen Reduktionsäquivalente. Auf der Grundlage der in dieser Studie untersuchten Chemikalien und Kraftstoffe lässt sich der durchschnittliche Energiebedarf pro vermiedenem CO_2 auf 10,2 MWh/t CO_2 für Chemikalien und 14,1 MWh/t CO_2 für Kraftstoffe berechnen. Der Energiebedarf umfasst den Bedarf an Strom, Wärme und Wasserstoff. Das vermiedene CO_2 basiert auf dem für das Zukunftsszenario ermittelten Potenzial zur Verringerung des CO_2-Fußabdrucks.

3 Introduction

Climate change remains an important topic, but achieving the targets for GHG reduction remains a challenge. North Rhine-Westphalia (NRW) represents the industrial core region of Germany, generating the highest gross domestic product of the federal states. Hence, it also is the home of many point sources for CO_2 emissions, several of them hard to replace with other technologies or even unavoidable ones. Additionally, the Rheinisches Revier (RR), the lignite producing and utilizing area between Aachen, Düsseldorf and Cologne, is facing a structural change caused by the coal exit plan as other parts of NRW have experienced with the closure of deep coal mining area by the end of 2018.

This study assesses the potential of CO_2 utilization (CCU) opportunities not only to recycle carbon and to reduce GHG emissions, but also to sustain the local industry and to establish new local industries based on sustainable technologies. Many commodities are carbon-based, but are currently of fossil origin or facing other sustainability challenges. Therefore, the focus of this study is to identify the potential of CO_2-based fuels, chemicals and alternative protein sources. The route to commercialization requires several steps, depending on technology level but also on commercial aspects. Therefore, implementation of CO_2-based products, needs to follow multiple development steps as shown in Figure 3-1.

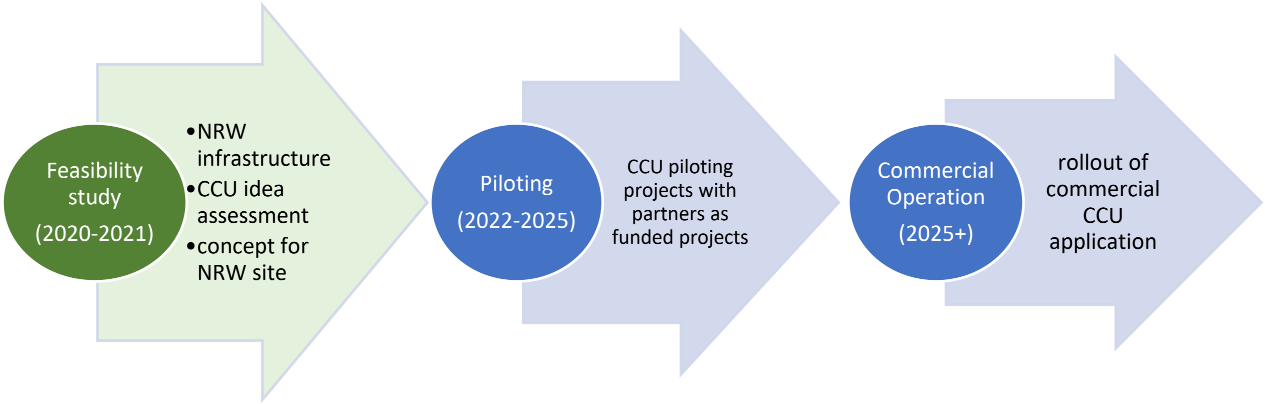

Figure 3-1: Envisioned phases towards implementing CO_2 utilization technologies.

The present study focuses on generating a solid basis for further pilot activities, as indicated by the left arrow in Figure 3-1. It is important to note that potential consortia for pilot activities are not pre-defined by this work and that the intention is to trigger more discussions on industrial but also political level on how to achieve transformation of the local industry to carbon neutrality. Hence, the study is divided into three parts:

Part A "Assessment of NRW infrastructure": summarizing the current situation within North Rhine-Westphalia in regard to infrastructure and main industries. This assessment is the basis for identifying those CCU options, which fit well into this region.

Part B "CCU idea ranking": this is the core part of this study, aiming to assess several CCU options using the same parameters to maintain comparability. The focus is on drop-in solutions, which would allow transforming existing value chains towards carbon neutrality by mainly replacing current fossil-based feedstocks. The assessment is done by a scoring matrix of a defined set of criteria. Applying the analytical hierarchy process (AHP method) provides a prioritization of the CCU ideas, accompanied by a sensitivity analysis to identify the major impact factors.

Part C “Concepts for a site in NRW”: exemplary concepts for a real site within NRW are developed to outline further development steps and costs towards commercialization. These concepts are considered to form the basis for potential follow-up pilot or demo projects.

The Partners:

German Aerospace Center (DLR e.V.)

The German Aerospace Center (DLR) is the national research center for aerospace and the German space agency. A total of around 10,000 employees work at 30 locations and in 55 institutes in the areas of aviation, space, energy and transport.

The Institute for Future Fuels, attributed to DLR’s field of energy, develops technologies in order to investigate the production of fuels and raw materials by renewable energy and in particular solar thermal methods. Being a former part of the Institute of Solar Research, the institute has many years of experience in the production of energy carriers such as hydrogen, as this can be used directly, for example in fuel cells, but is also necessary for the production of hydrocarbon-based liquid or gaseous energy carriers and chemical intermediates. The goal is to allow a broader use of solar energy in industrial sectors aside from electricity production, for which it is already state of the art. This is pursued through detailed modelling work of solar components, such as reactors and receivers, but also of whole processes for the production of fuels and chemicals, which have to be modified for using solar energy. Furthermore, two solar simulators and a solar furnace, located in Jülich and Cologne, provide the opportunity to validate simulations with experimental data.

Uniper SE

Uniper is an international energy company with around 12,000 employees in more than 40 countries. The company plans to make its power generation CO_2-neutral in Europe by 2035. With about 35 GW of installed generation capacity, Uniper is among the largest global power generators. Its main activities include power generation in Europe and Russia as well as global energy trading, including a diversified gas portfolio that makes Uniper one of Europe’s leading gas companies. In 2020, Uniper had a gas turnover of more than 220 bcm. Uniper is also a reliable partner for municipalities, public utilities, and industrial companies for developing and implementing innovative, CO_2-reducing solutions on their way to decarbonizing their activities. As a pioneer in the field of hydrogen, Uniper is active worldwide along the entire value chain and is implementing projects to make hydrogen usable as a mainstay of energy supply.

The Innovation department has several focus topics, to identify new business segments for Uniper. Carbon Recycling has been a core focus area since Uniper was formed in 2016. Prior to that, the innovation and technology team has been active in several European funded Carbon Capture (and Storage) projects and built and operated a non-funded carbon capture pilot plant at Uniper’s coal-fired station in Wilhelmshaven, separating 2.8 t/h of CO_2.

4 Part A: Assessment of NRW Infrastructure

The first part of this study introduces the considered location and analyses its boundary conditions. The focus is put on the state of North Rhine-Westphalia and especially the Rheinisches Revier, which is currently a core region for lignite mining and power plants. In Figure 4-1 below, the boundaries of the state are shown together with a highlight of the Rheinisches Revier. The definition used for the region is taken from the funding conditions for coal regions of the Federal Ministry of Economic Affairs and Energy (BMWi).[19]

Initially, an overview of the industry, power supply and demand will be given. After identifying the CO_2 emission sources, transport routes and pipelines will be discussed. The first part will be concluded with an overview of the agricultural sector and a representation of all relevant infrastructure in a map.

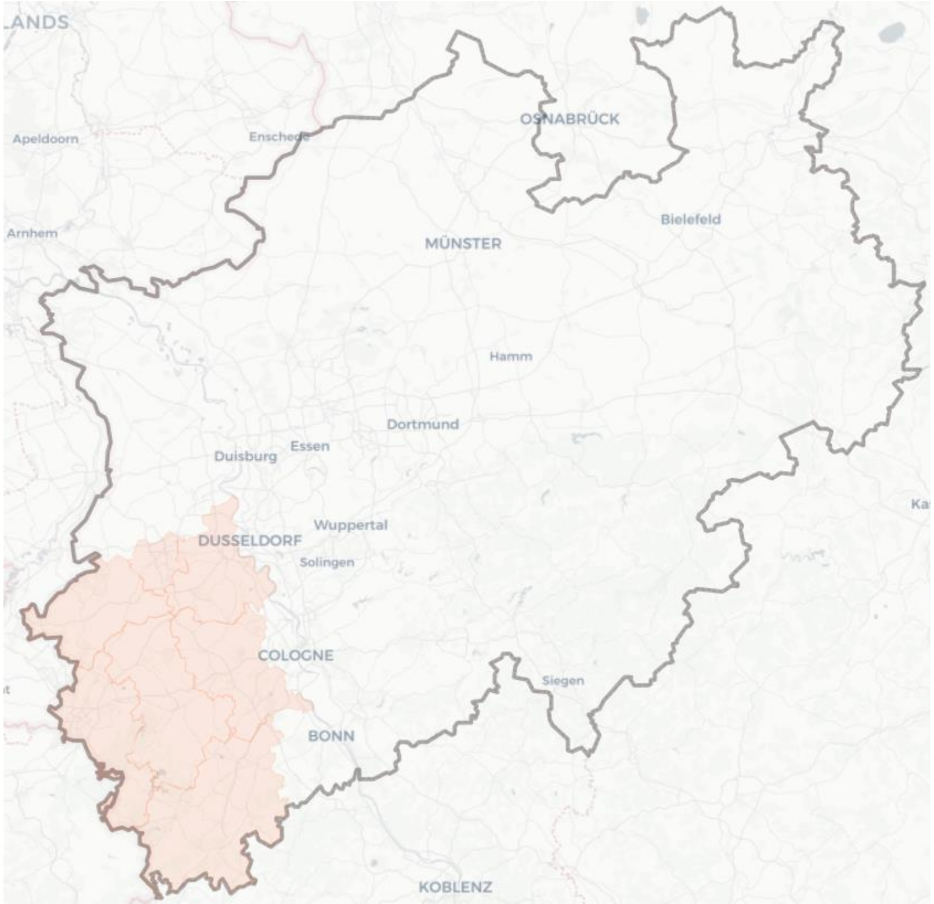

Figure 4-1: Map of NRW with the eligible funding region Rheinisches Revier marked in orange, defined through the Strukturstärkungsgesetz Kohleregionen.[19,20]

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[19] BMWi, Strukturstärkungsgesetz Kohleregionen, published 8. August 2020

[20] OSM Positron (Carto) Map tiles by CartoDB, under CC BY 3.0. Map data © OpenStreetMap contributors under ODbL. uMap project provided the editor, regional boundaries obtained from OpenDataLab with data from Geodatenzentrum © GeoBasis-DE / BKG 2018.

4.1 Industry in NRW

NRW is the industrial core region of Germany, generating the highest gross domestic product of the federal states. About 20% of the working population is employed in the industry sector, generating approximately 27% of the gross value added. Relevant industrial sectors are the mechanical engineering, chemical industry, food industry, metal production & processing and the automotive sector, as depicted in Figure 4-2.[21] Additionally, the health care services and IT/communication technology sector plays an important role.

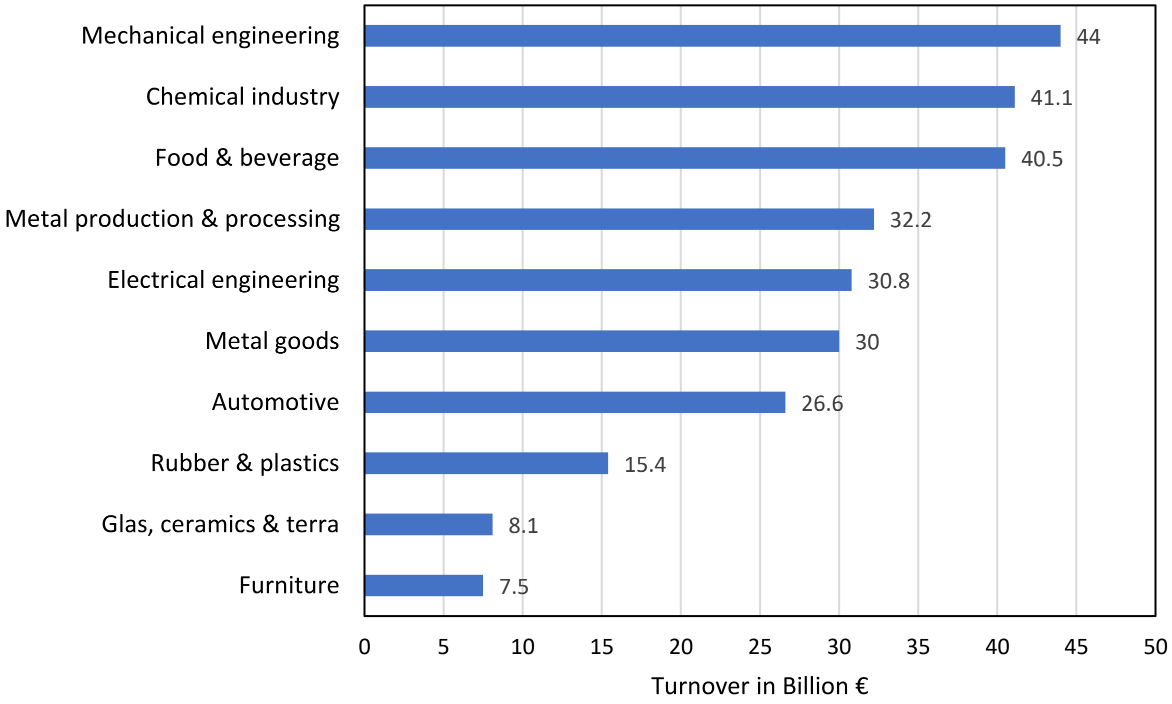

Figure 4-2: Turnover in NRW by sector in 2020 (based on IT.NRW data, includes companies with at least 20 employees per sector).[21]

4.1.1 Chemical Parks within Rheinisches Revier

Most chemical production facilities are located in industrial chemical parks, of which 13 exist in NRW. Those chemical parks are mainly located close to the river Rhine or in the northern Ruhr area. Only three chemical parks are located within the Rheinisches Revier: BIZZPARK close to Heinsberg, CHEMPARK in Dormagen and Chemiepark Knapsack close to Hürth. All three are partners of the initiative ChemCologne.[22]

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[21] https://www.nrwinvest.com/de/standort-nrw/das-spricht-fuer-nrw/deutschlands-industrielle-kernregion/, accessed 23.09.2021

[22] https://www.chemcologne.de/investieren-im-rheinland/chemieparks-freiflaechen.html, accessed 23.09.2021

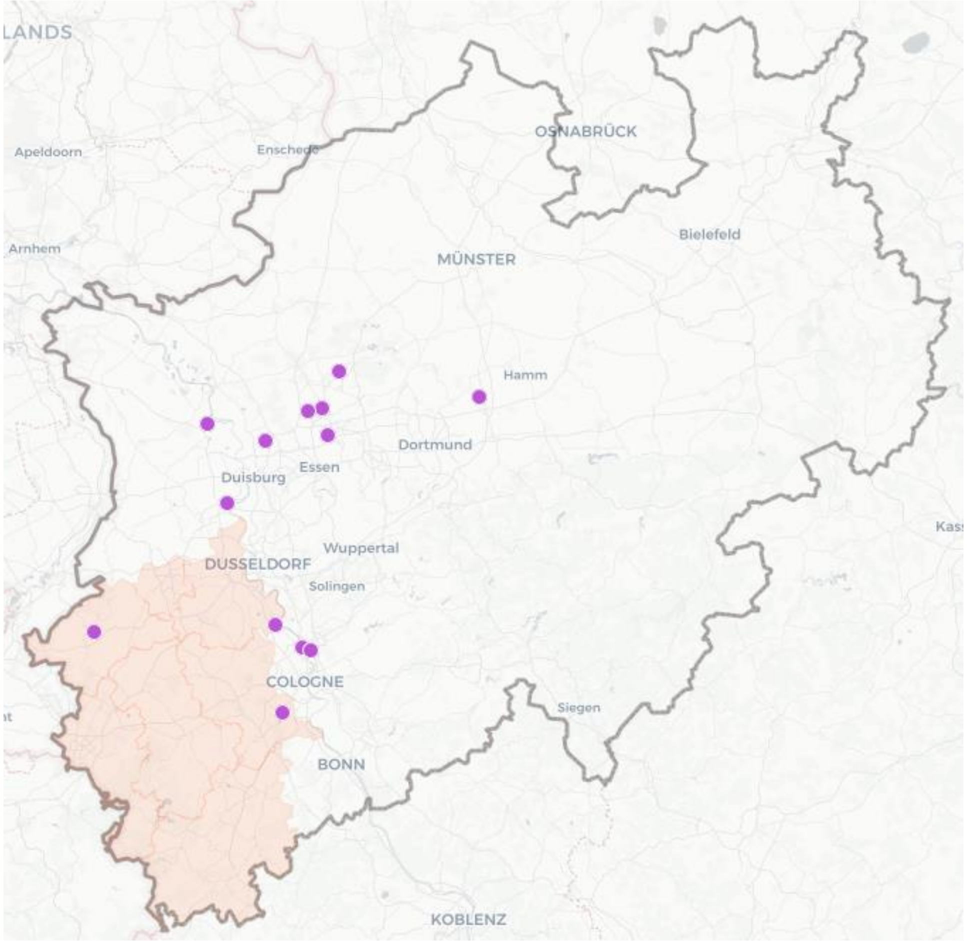

Figure 4-3: Location of chemical parks in NRW.[19,20,23]

BIZZPARK Oberbruch

The Oberbruch industrial park was founded in 1998 and is operated by the waste management company Veolia Industriepark Deutschland GmbH.[24] Veolia supplies the utilities to the companies on site, provides logistics and sewage treatment. About 1,000 employees are working at the park.[25] The chemical company Toho Tenax Europe GmbH produces fibers based on carbon. The total area of the park is about 100 ha, with about 24 ha still being available for construction. One advantage is the proximity to big industrial regions such as Cologne and Düsseldorf as well as to the harbors Antwerpen and Rotterdam.

CHEMPARK Dormagen

The CHEMPARK Dormagen was founded in 1917 and is operated by Currenta GmbH & Co. OHG.[26] About 9,500 employees are working at the park, where the production is focused on pesticides, polymers plastics

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[23] Chemieatlas, https://maps.chemieatlas.de/, accessed 23.09.2021

[24] https://www.aachener-zeitung.de/allgemeines/bizzpark-oberbruch-neuansiedlungen-sind-das-erklaerte-ziel_aid-25299021, accessed 23.09.2021

[25] https://www.veolia.de/industriepark, accessed 23.09.2021

[26] https://www.chempark.de/de/chempark-dormagen.html, accessed 27.09.2021

and rubbers. A high number of chemical companies are located at the site, among others Bayer CropScience AG, Covestro Deutschland AG and LANXESS AG. Chemicals which are used and produced include chlorine, toluol, benzol, ethylene, ammonia, propylene and butadiene.[27] The total area of the park is about 360 ha, with about 0.5-6 ha being available.

Chemiepark Knapsack

The chemical park was founded in 1907 in Knapsack. An extension was followed in the period 1960-1969.[28] Currently it is operated by YNCORIS GmbH & Co. KG, which provides utilities and plant construction services. About 2,500 employees are working at the park.[29] A waste-to-energy plant is located at the site, owned by the eew Energy from Waste Saarbrücken GmbH. Several chemical companies are producing at the site, among others BASF SE, Bayer AG, Clariant AG, CABB Group GmbH and Lyondellbasell Industries AG. Products are formic acid, propylene, ethylene, acetic acid, polypropylene (PP) and polyvinyl chloride (PVC). The total area of the park is about 180 ha with 20 ha being available for construction. An expansion of the site is currently ongoing.[30]

4.1.2 Refineries

There are two refinery sites located in NRW: Shell in the Cologne area and BP in the Gelsenkirchen area. They represent the two of the three largest refinery sites in Germany, with a combined processing capacity of about 30 million t/a of crude oil[31] and a combined workforce of about 4,900 employees.

The Shell Rheinland Refinery located in Cologne and Wesseling is the largest refinery in Germany, processing 17 million t/a crude oil, supplied via the North-West-Pipeline and via the Rotterdam-Rhine-Pipeline. About 3,000 people work at the two sites.[32] Main products are fuels, fuel oils, and petrochemicals. Several companies are in close proximity to the refinery for a direct supply of their raw material, e.g., Braskem Europe GmbH to produce 225,000 t/a of polypropylene and LyondellBasell, producing together with its plants at Knapsack 2.2 Mio t/a of polyolefins.

The BP refinery in Gelsenkirchen is the third largest refinery in Germany, processing about 12 million t/a crude oil. About 1,900 people are working at the two sites.[33] The major products are fuels (7,000 kt/a), petrochemicals (3,090 kt/a) and fuel oil (950 kt/a). There is a direct pipeline to the chemical park in Marl for the C4 fraction (550 kt/a).[34]

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[27] https://www.chemcologne.de/investieren-im-rheinland/chemieparks-freiflaechen/chempark-dormagen.html, accessed 27.09.2021

[28] https://www.chemiepark-knapsack.de/standort/historie/?L=46, accessed 23.09.2021

[29] https://www.chemcologne.de/investieren-im-rheinland/chemieparks-freiflaechen/chemiepark-knapsack.html, accessed 23.09.2021

[30] https://www.chemiepark-knapsack.de/, accessed 23.09.2021

[31] https://www.mwv.de/raffinerien-und-pipelines/, accessed 27.09.2021

[32] https://www.shell.de/ueber-uns/projects-and-sites/shell-rheinland.html, accessed 27.09.2021

[33] https://www.bp.com/de_de/germany/home/wo-wir-sind/raffinerie-gelsenkirchen/wer-wir-sind/zahlen-und-fakten.html, accessed 27.09.2021

[34] https://www.bp.com/de_de/germany/home/wo-wir-sind/raffinerie-gelsenkirchen/wer-wir-sind/zahlen-und-fakten.html, accessed 23.09.2021

Hydrogen is essential for crude oil upgrading in several process steps. Currently, hydrogen is produced on the refinery sites from fossil feedstocks, e.g., natural gas, via steam methane reforming process, significantly contributing to the overall CO_2 footprint of the sites. Both NRW-based refineries are actively pursuing green hydrogen projects: in the REFHYNE project, Shell installed a 10 MW PEM electrolyzer at their site in Wesseling for the on-site production of green hydrogen.[35] In the GetH2 project, BP is working with partners to transport green hydrogen produced in Lingen, Northern Germany, via existing natural gas pipelines to their Gelsenkirchen site.[36]

4.1.3 CCU Activities in NRW

CO2 utilization is recognized by many industrial players as relevant for future feedstock sourcing and also to mitigate unavoidable CO_2 emissions. Since new technologies typically start with R&D activities, many activities were and are ongoing on research level. In the past 10 years, several research activities have been developed to pilot activities, but further development has stopped often after a funded project was completed. Currently, there are some activities at pilot scale within NRW, which are summarized in a non-exhaustive overview in Table 4-1.

Table 4-1: Examples of CCU pilot activities within NRW.[37]

Project	Focus	Site	Partners
ALIGN CCUS & TAKE-OFF	CO_2-based fuels	Niederaußem	RWE, Mitsubishi Power Europe, Asahi Kasei
Carbon2Chem	Methanol and Ammonia	Duisburg	17 partners from economy (steel, chemistry and energy) and research, project leader is Thyssenkrupp
Cardyon	CO_2-based polyols	Dormagen	Covestro AG
Rheticus	CO_2-based chemicals (butanol and hexanol)	Marl	Evonik AG, Siemens AG

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[35] https://www.shell.de/ueber-uns/shell-energie-dialog/refhyne-eroeffnung.html, accessed 27.09.2021

[36] https://www.get-h2.de/umsetzung/, accessed 27.09.2021

[37] https://www.in4climate.nrw/best-practice/projekte/, accessed 23.09.2021

4.2 Power Supply, Usage and Demand

More than 200 power plants are located within North Rhine-Westphalia, including renewables. The installed electrical capacity is about 42 GW, with the major contributors being lignite (10.4 GW), natural gas (8.4 GW), hard coal (7.8 GW), on-shore wind (6.0 GW) and solar (5.7 GW).[38] The Rhine area is dominated by lignite-fired power stations, while gas and hard coal power plants are located in the remaining parts of NRW.

The total gross electricity consumption sums up to 144.5 TWh in the year 2018. At the same time, 150.9 TWh of electricity have been produced. In Figure 4-4, the contribution of different energy carriers to the gross electricity production in NRW in 2018 is depicted. It is obvious that fossil energy carriers still account for the major share in electricity supply, with 47.9% provided from lignite-powered plants, 17.3% from hard coal, and 13.9% from gas. Over a decade, the share of renewables increased from 4.4% in 2008 to 13.6% in the year 2018.

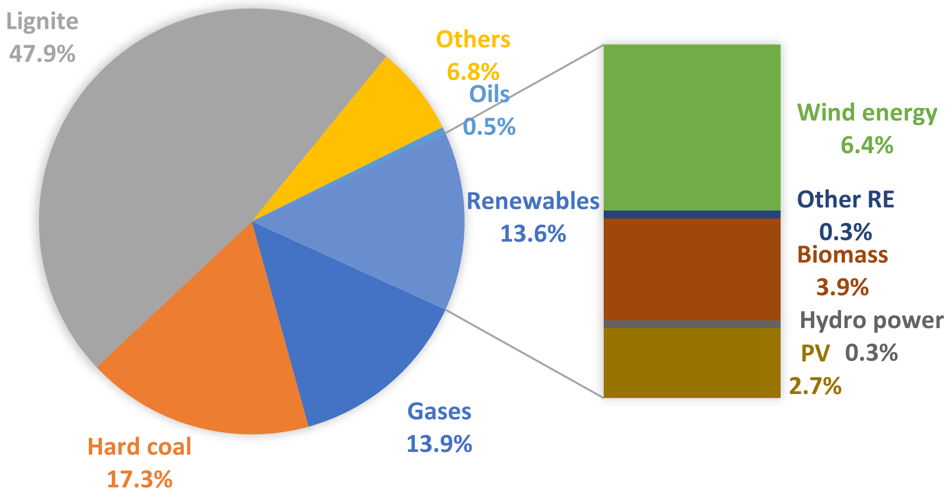

Figure 4-4: Gross electricity production in NRW in 2018.[39]

In NRW, the final energy demand of 588.7 TWh is allocated 38.8% to industry, 23.9% to the transport sector, 24.3% to households and 13% to the commercial, trade and services sector in the year 2018.[39] The industry sector covers its energy demand mainly by gas (35.7%), electricity (26.8%), and hard coal (16.8%). Direct renewable energy integration accounts for only 1.6%.[39]

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[38] Kraftwerksliste der Bundesnetzagentur https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Versorgungssicherheit/Erzeugungskapazitaeten/Kraftwerksliste/start.html, accessed 23.09.2021

[39] Energieatlas.NRW, https://www.energieatlas.nrw.de/site/werkzeuge/energiestatistik, accessed 23.09.2021

4.2.1 Rheinisches Revier: Coal fired Power Plants and Mining

Three large lignite power plant sites are located in the Rheinisches Revier: Neurath (4.4 GW installed), Niederaußem (3.6 GW installed) and Weisweiler (2.1 GW). Several open pit mines in the Rheinisches Revier provide lignite for the lignite-fired power plants operated by RWE Power AG. The largest lignite deposits are Hambach (1,350 million), Garzweiler (1,100 million t lignite) and Inden (260 million t lignite). Hambach is located in the region of Niederzier, district Düren, Elsdorf and Rhein-Erft-district. The mining started in 1978 and is expected to stop in 2030.[40] The open pit mine Garzweiler is located in the district Rhein-Kreis Neuss and Heinsberg, originally starting from Grevenbroich around 100 years ago. The mining will continue after 2030 to provide lignite for the remaining power plants. In 2017, 3,200 ha operational area were used for mining, while 11,400 ha have been approved in total.[41] The open pit mine Inden in the district of Düren and Aachen provides lignite for the power plant in Weisweiler, operated by RWE Power AG.[42] By 2030, the open pit mine will be mined-out, which also implicates the stop of the power plant Weisweiler. Until then the operational area of 1,700 ha (in 2017) will be expanded to the approved area of 4,500 ha.[43]

4.2.2 Renewable Energies

The spatial distribution of operated renewable energy plants in the Rheinisches Revier is depicted in Figure 4-5. Wind turbines are equally distributed in the rural area of NRW and also in the RR, excluding nature reserve areas (highest density is south of Paderborn). In total, 3,764 wind turbines provide an installed power of 6,187 MW by end of 2020 in NRW, which produced 12,301 GWh. Currently, 40 more wind power plants are approved in RR, increasing the installed power by 177.4 MW.[36] Biomass plants can be found throughout NRW. In total, 1367 units are in operation, with an installed capacity of 894 MW. The electricity production sums up to 5,349 GWh in 2019.[36] Photovoltaic units are mainly installed on roof areas (281,959 units with 5,106 MW in NRW by end of 2019) and to a smaller extent on open areas (355 units with 272 MW in NRW by end of 2019). The units' locations are evenly distributed in NRW, excluding nature reserve areas or woodland, and produced approximately 4,775 GWh in 2019.[45] Hydro power plays only a minor role in NRW with 430 units providing about 190 MW of power. 60% of this power is produced in the region Arnsberg, which is located in the eastern part of NRW. Two hydropower storages exist there with a capacity of 300 MW.[44]

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[40] https://www.group.rwe/investor-relations/news-und-ad-hoc-mitteilungen/news/news-2020-01-16, accessed 23.09.2021

[41] https://www.group.rwe/unser-portfolio-leistungen/betriebsstandorte-finden/tagebau-garzweiler, accessed 23.09.2021

[42] https://www.rwe.com/investor-relations/news-und-ad-hoc-mitteilungen/news/news-2020-01-16, accessed 23.09.2021

[43] https://www.group.rwe/unser-portfolio-leistungen/betriebsstandorte-finden/tagebau-inden, accessed 23.09.2021

[44] https://wasserkraftwerke-nrw.de/wasserkraft/, accessed 23.09.2021

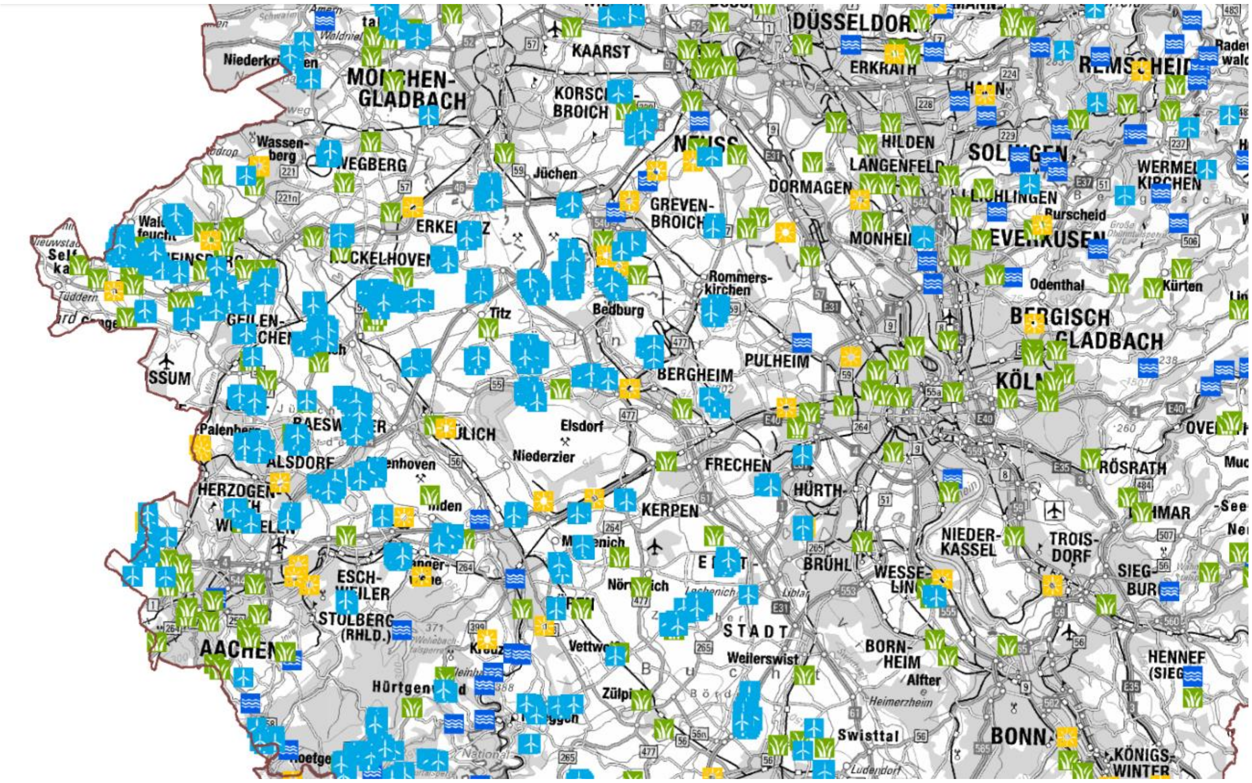

Figure 4-5: Spatial distribution of operated wind power plants (bright blue), biomass plants (green), PV open area installation (yellow), and hydro power plants (dark blue) in the Rheinisches Revier, NRW.[45]

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[45] https://www.energieatlas.nrw.de/site/bestandskarte, Energieatlas NRW, Publisher: Landesamt für Natur, Umwelt und Verbraucherschutz NRW based on data from Bundesnetzagentur, Geobasis.NRW, ISA, Landesverband Erneuerbare Enigien NRW e.V., Amprion GmbH, TenneT B V, QUIS, Stauanlagen-Datenbank NRW, Potenzialstudie der Bezierksregierung Arnsberg (2013), accessed 23.09.2021

4.3 Location of CO_2 Emissions

The European Pollutant Release and Transfer Register (E-PRTR) provides a Europe-wide register with key environmental data from industrial facilities. CO_2-emitters are included with a minimum emission of 100 kt of CO_2 per year, covering about 90% of total CO_2-emissions. According to the database, the emissions in the year 2017 in NRW accumulated to 210.5 Mt of CO_2. The major CO_2 emitters of industry in NRW are the lignite-fired power plants with a share of 30%. The steel and iron industry has a share of 18%, followed by natural gas (16%) and hard coal (14%), see Figure 4-6.

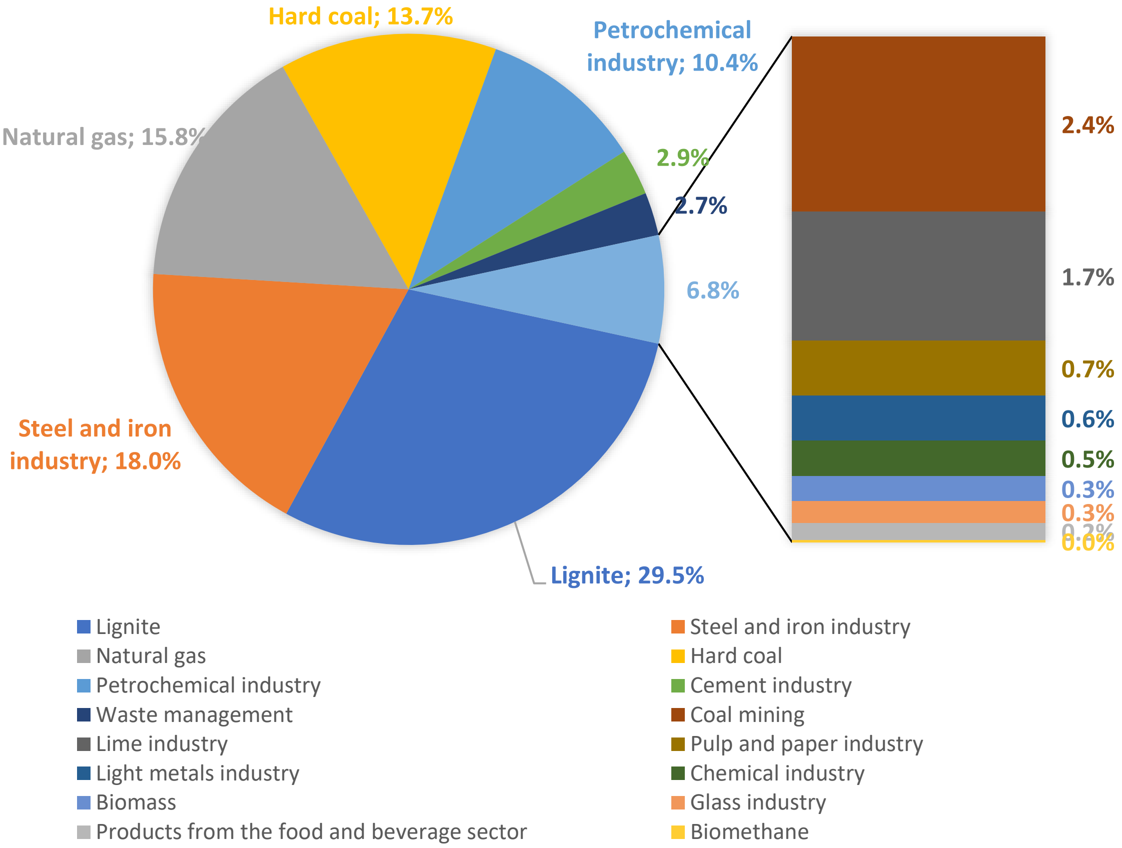

Figure 4-6: Share of CO2-emissions by industrial sector in NRW for 2017.[46]

The following Figure 4-7 shows the location of the facilities and scales the marks according to their emissions. The lignite power plants are located in the core of the Rheinisches Revier, while gas and hard coal-fired plants are mostly distributed along the rivers Rhine, Emscher and Lippe. The impact of the rivers on the industries' spatial distribution gets obvious once the steel, petrochemical and chemical industries are considered. Big emitters are seldomly found far away from these rivers, except lignite coal power plants which are close to the mines. For example, the iron and steel industry are located in Duisburg and the surrounding area, and chemical plants are mainly along the river Rhine and in Gelsenkirchen or Marl. In contrast, the cement plants are distributed in the district of Soest and biomethane upgrading plants are spaced out with a focus on the western part of NRW. Figure 4-7 clearly illustrates that the lignite power

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[46] E-PRTR, https://prtr.eea.europa.eu/, accessed 23.09.2021

plants, located in the Rheinisches Revier, are NRW's biggest CO_2 emitters (Neurath: 29.9 Mt CO_2, Niederaußem: 27.2 Mt CO_2) next to the power plant close to Aachen with mixed energy carriers being natural gas and lignite (Eschweiler: 19.1 Mt CO_2). Lower amount of CO_2 emissions could be captured from biomethane upgrading plants, however, at a higher purity resulting in higher capture efficiency. Further studies need to determine if acquiring pure CO_2 emissions from widespread small point sources is more economically and ecologically viable than from lower concentrated but larger point sources. Thus, for CCU pilot applications biomethane upgrading plants could be a feasible option, but maybe not for commercial CCU applications due to the economies of scale.

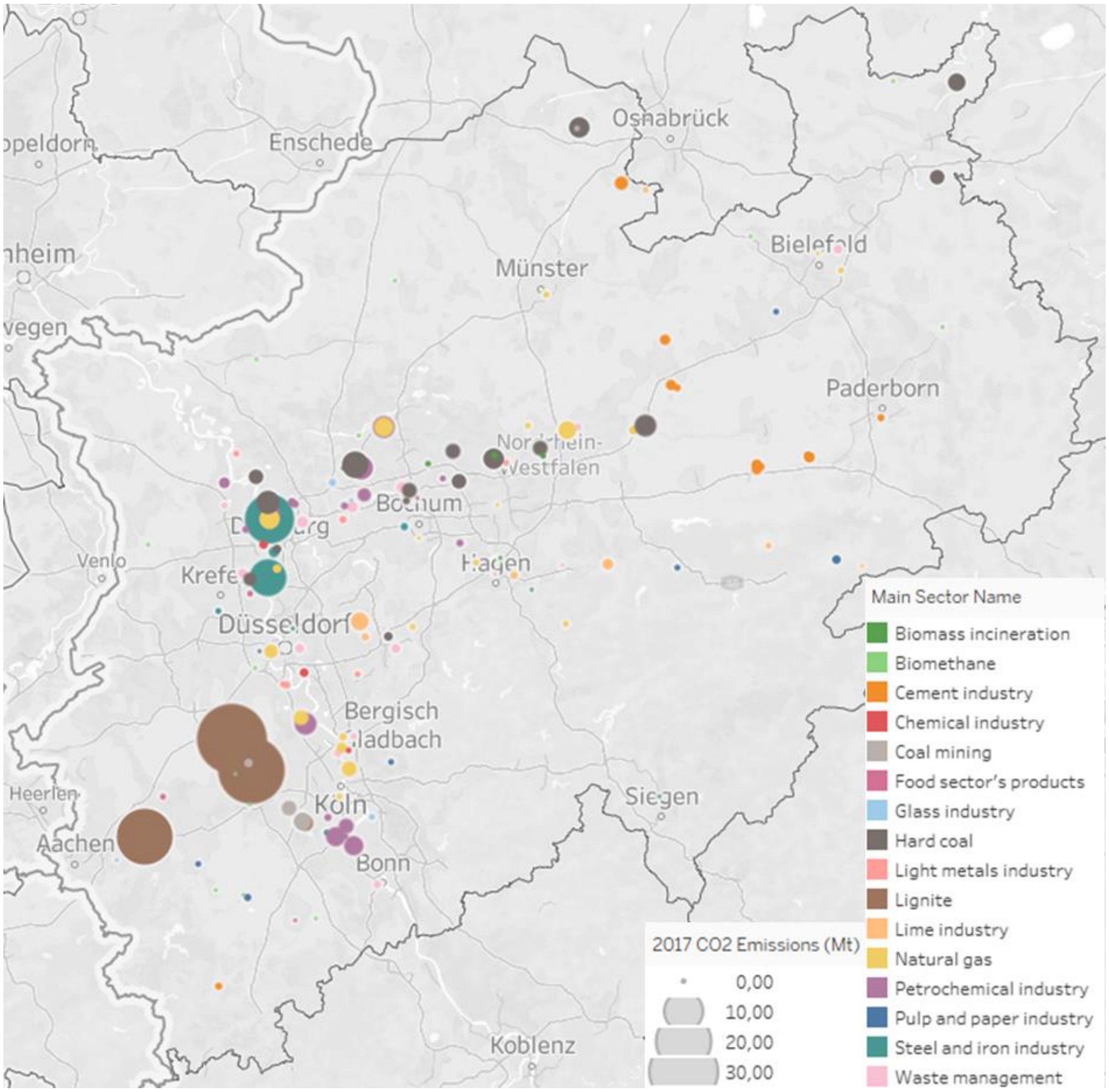

Figure 4-7: Location of CO2-emission sources in NRW, separated by industry. Emission quantities are given for the year 2017.[47]

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[47] Map utilizes data from E-PRTR[46] including information on industry according to NACE code and from IEA Bioenergy (http://task37.ieabioenergy.com/about-task-37.html), accessed 23.09.2021. The map was created in Tableau Public.

4.3.1 Future Development of Available CO_2 Emissions

The coal exit plan will alter the share of the contributors to CO_2 emissions and the overall amount of CO_2 emissions in NRW drastically. However, its effect on the industrial contributors to CO_2 emissions (see Figure 4-6) will vary, since each sector has different process-related emissions. According to a study by Agora Energiewende process-related emissions account for 32% in the steel industry, 18% in the petrochemical industry, and 65% in the cement industry.[48] Thus, incorporating renewable energy into the production would have the biggest impact in the petrochemical industry and the least in the cement industry due to the high process inherent emissions. Prospective emissions per sector are depicted in Figure 4-8 for NRW, if only process emissions are considered. As a result, the steel and iron industry will be the major CO_2 emitters in the year 2050 in NRW, followed by the cement and lime industry. However, this does not consider any change in the used fuels or processes.

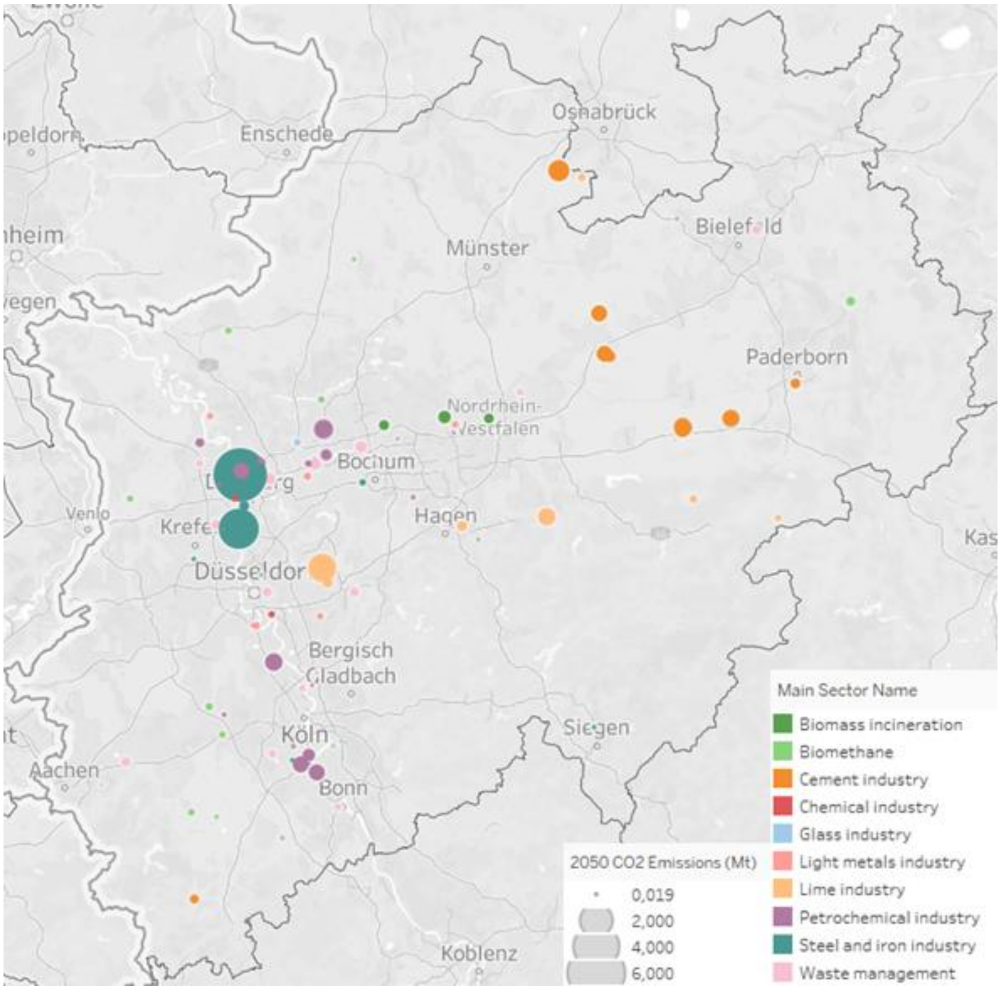

Figure 4-8: Location of CO_2-emission sources in NRW, separated by industry. Emission quantities are given for the year 2050.[47] It is considered that all lignite and hard coal power plants are shut down and remaining industrial emissions are due to the current process emissions.[48]

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[48] Agora Energiewende und Wuppertal Institut (2019): Klimaneutrale Industrie: Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement. Berlin, November 2019.

4.4 Traffic Routes

The state of North Rhine-Westphalia offers a dense transportation infrastructure in the form of inland waterways, roads and railways and airports. The major amount of goods is transported via road, accounting for 79% transported weight in Germany in 2018. Next to road traffic, the transportation via railway (8.5% of transported weight in 2018), inland waterways (4.2% transported weight in 2018) and sea transport (6.3% transported weight in 2018), and to smaller extent air freight (0.1% of transported weight in 2018) are of importance in Germany.[49]

Except for coal, raw oil or methane, goods are mainly transported via truck on roads.[50] An important combined transport point is located at Cologne-Eifeltor, where goods are transferred between train/ship and trucks.

4.4.1 Water Ways

The river Rhine has the highest traffic density of goods (tkm/length of waterway in km) of all inland waterways in Germany, especially between Cologne and Duisburg.[51] Furthermore, the river Rhine has the highest classification of inland waterways (VIc), which allows “Große Rheinschiffe” boat size and pushing units composed of up to 6 lighters. The Rhine connects upstream (South) of Bonn to areas with major chemical industry (Rhine-Main, Rhine-Neckar, Basel), and via the Rhine-Main-Danube-channel to major industrial centers, e.g. Frankfurt, Nuremberg, Linz, and further south via the river Danube to Vienna, Hungary, Rumania, Bulgaria and the Black Sea. Downstream from Emmerich river Rhine flows through the Netherlands and to the port of Rotterdam, which is one of the biggest sea ports of the world. The Wesel-Datteln-channel and Rhine-Herne-channel are connected to the river Rhine and thus connect central NRW to this important inland waterway. Both channels meet at Dortmund and, thus, offer the connection to the Dortmund-Ems-channel, which allows the water way transport to the North Sea ports of Emden, Bremen, and Hamburg, but also to the industrial centers in Hanover (including Peine and Salzgitter) and Berlin via the Mittelland-channel. The connection of channels and rivers and potential ports for heavy cargo handling are displayed in Figure 4-9.

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[49] https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Gueterverkehr/Tabellen/gueterbefoerderung-lr.html, accessed 23.09.2021

[50] Transported goods in Germany for different transportation categories and goods categories (NST-2007) in 2018:https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Transport-Verkehr/Gueterverkehr/Tabellen/verkehrstraeger-gueterabteilung-a.html, accessed 23.09.2021

[51] Bundeswasserstrassen – Güterverkehrsdichte der See- und Binnenschifffahrt 2000 auf dem Hauptnetz der Bundeswasserstraßen, Bundesministerium für Verkehr und digitale Infrastruktur, https://www.gdws.wsv.bund.de/SharedDocs/Downloads/DE/Karten/Karten_neu/w172b_Verkehrsdichte.pdf?__blob=publicationFile&v=1, accessed 23.09.2021

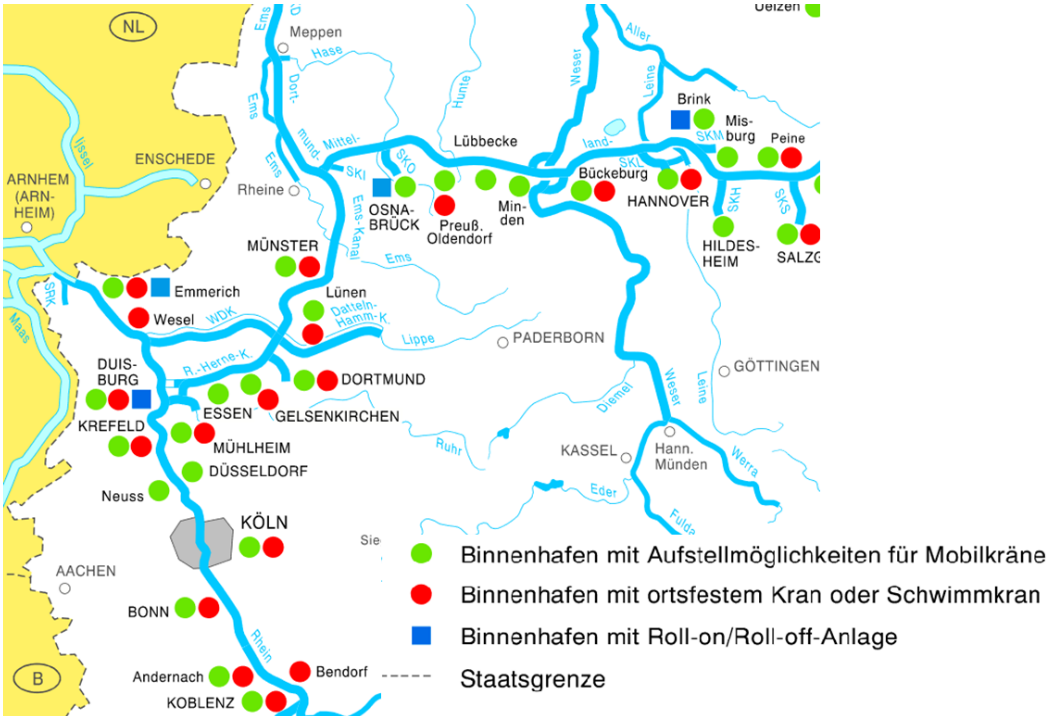

Figure 4-9: Federal Waterways in North Rhine-Westphalia and surrounding states showing inland ports for heavy cargo handling.[52]

4.4.2 Transported Goods

The main categories of transported goods on inland waterways in Germany are: Ores and stones, coal and mineral oil, coking plant and mineral oil products, and chemical products. In 2019, 205 million t of goods were transported on inland waterways in Germany, including import, export, and transit traffic, out of which 23.3 million t was coal.[53] In total, the transportation of coal, mineral oil or natural gas account for 11.4% (see Figure 4-10) of transported goods on waterways in 2019, from which the import had a share of 84%.[54]

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[52] © Bundesministerium für Verkehr und digitale Infrastruktur, Januar 2014 , Kartenbezeichnung: "W 166 b" Bundeswasserstrassen – Binnenhäfen mit Schwergutumschlag (w166 b), Source: Kartographie: Fachstelle für Geoinformationen Süd, Regensburg, https://www.gdws.wsv.bund.de/DE/service/karten/01_karten/karten-node.html, accessed 23.09.2021

[53] Genesis Destatis Table 46321-0005, available at https://www-genesis.destatis.de/genesis/online

[54] Genesis Destatis Table 46321-0008, available at https://www-genesis.destatis.de/genesis/online

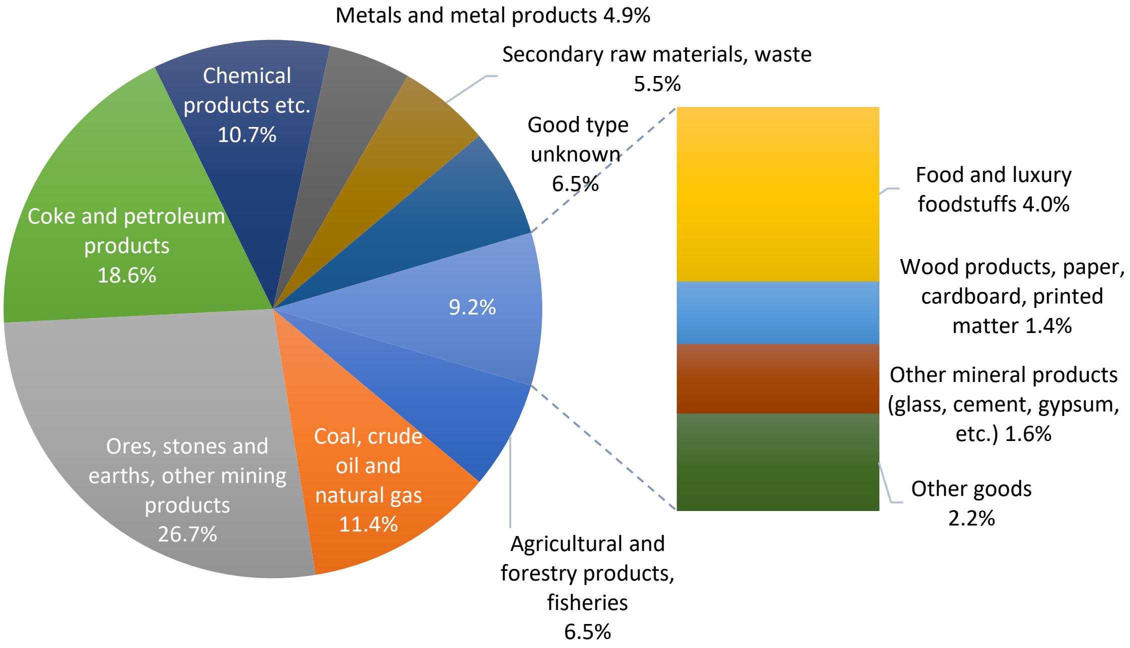

Figure 4-10: Transported goods on inland waterways in Germany in 2019.[55]

Duisburg is not only the biggest port in NRW, but also the biggest inland port worldwide[56], with 43.5% of goods of 110 million t total being handled at ports in NRW in 2019.[57,58] The Rheinisches Revier is situated in the administrative districts Cologne and Düsseldorf with the two ports Cologne and Bonn. There, mainly coking and mineral oil products (72%) and chemical products (27%) were handled between the two ports with a total capacity of 1.28 million t in 2019.[59] The main export district of Cologne in NRW is the administrative district Düsseldorf, which received 0.26 million t coking plant and mineral oil products and 0.42 million t chemical products from Cologne in 2019.[59] Dangerous cargo (mineral oil, toxic chemicals, LPG (Liquified Petroleum Gas), LNG (Liquified Natural Gas) is allowed on all major waterways in NRW. The distribution of handled goods at port Duisburg and Cologne is compared in Figure 4-11.

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[55] Genesis Destatis Table 46321-0008, available at https://www-genesis.destatis.de/genesis/online
[56] https://www.duisport.de/hafeninformation/, accessed 27.09.2021
[57] Genesis Destatis Table 46321-0014, available at https://www-genesis.destatis.de/genesis/online
[58] Genesis Destatis Table 46321-0015, available at https://www-genesis.destatis.de/genesis/online
[59] Genesis Destatis Table 46321-0012, available at https://www-genesis.destatis.de/genesis/online

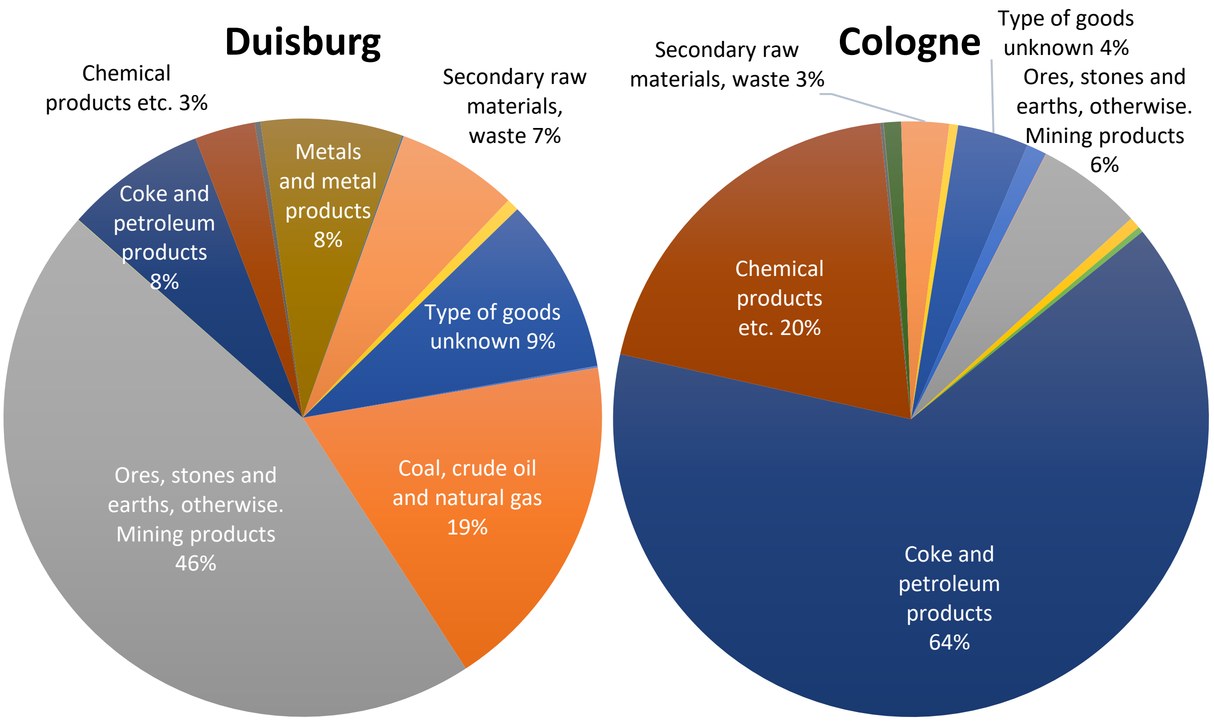

Figure 4-11: Handled categories of goods at the port Duisburg (left) and Cologne (right) in 2019.[60]

4.4.3 Railway and Road System

NRW has a well-developed system of rails for cargo trains. The main rail tracks in North-South direction are the two lines on both sides of the Rhine from the Southern state border at Bonn to Duisburg. In East-West direction the two lines from Dortmund to Duisburg are at the heart of the Ruhr industrial area. Furthermore, connecting lines to neighbor states allow for a national and European-wide exchange of goods via rail, e.g. with the Netherlands and in particular the port of Rotterdam in north-western direction, with Switzerland and Italy in southern direction via the industrial areas of Hesse, Rhineland-Palatinate, Baden-Württemberg, and Bavaria, or with Poland via Hanover and Berlin in eastern direction. In addition, the train station of Duisburg is the end point of the 11,000 km long “new silk road”, which starts in Chongqing in China.

On rails in NRW 9% of all goods were transported in 2018. In the administrative district Cologne mainly coking plant and mineral oil products (22%) and waste products (22%) were transported via railway with a total capacity of 1.54 million t in 2019.[61] The main export district of Cologne in NRW is the administrative district Düsseldorf, which received 0.20 million t chemical products from the district Cologne in 2019. However, 57.9% of the transported goods with a starting railway station in the district Cologne and an end railway station in NRW were of unspecified content.[61]

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[60] Genesis Destatis Table 46321-0015, available at https://www-genesis.destatis.de/genesis/online

[61] Genesis Destatis Table 46131-0013, available at https://www-genesis.destatis.de/genesis/online

NRW has a well-developed road infrastructure with 29,545 km road length (excluding roads in cities). Especially the center of NRW between Cologne-Duisburg and Dortmund has the highest density of federal roads in Germany.[62] Freight trucks transport mainly agricultural and forestry products or other raw materials in Germany (35% of transported weight), or mineral, chemical and petroleum products (20%).[63]

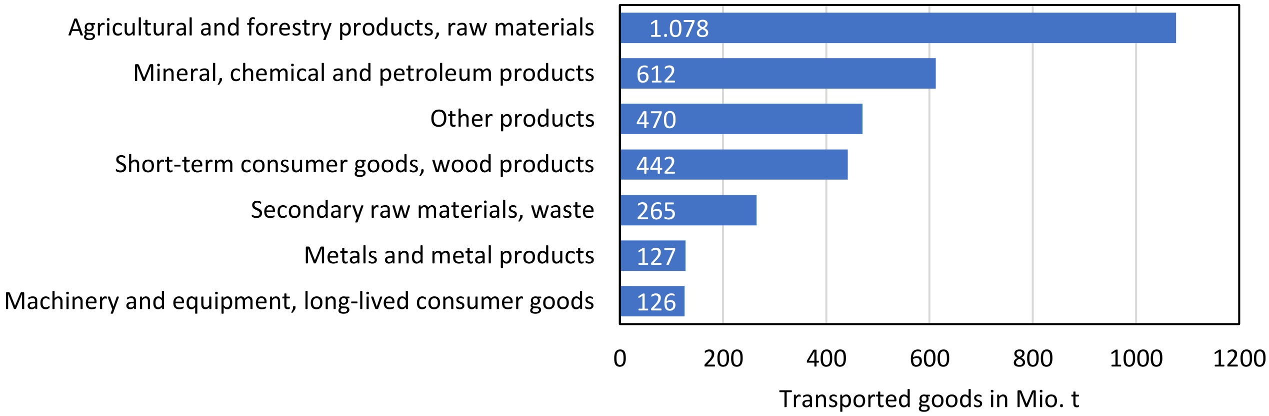

Figure 4-12: Transported goods with freight trucks in Germany in 2020.[63]

4.4.4 Future Development

With the decreasing use of lignite and hard coal in power plants, free freight capacities due to the discontinuation of coal transport might open up. These could be used to distribute CCU-based products instead. However, different types of vessels will be required depending on the CCU product in question. On the railway, the coal phase out could reduce the outgoing freight in the administrative district of Cologne by at least 2.7% of which 69% is currently redistributed within the administrative district.[64] In Germany the NST product group including coal, crude oil and natural gas accounted for 8% of transported goods on railway in 2019.[65] On inland waterways, 23.3 million t of coal was transported in Germany in 2019, which equaled 11% of all transported goods on inland waterways.[66] Thereof, the major share is imported (84%) or transported within Germany (13.9%). Only 0.6% of coal transported on inland waterway was exported, or passes Germany as transit traffic (1.6%).[67] In NRW, 661,096 t of coal was sent from ports in NRW on inland waterways to German administrative districts. Here, a major contribution is coal transport from the administrative district Düsseldorf to Arnsberg (43.3%) and Münster (30.3%). Besides that, coal is sent from ports in NRW to France (3,140 t), Belgium (51,396 t), and the Netherlands (60,228 t).[68]

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[62] Map of federal roads in Germany classified according to their function (0: connects metropolitan areas, I: connects regional metropolis among each other or regional metropolis to metropolitan areas) https://www.bmvi.de/SharedDocs/DE/Artikel/StB/Verbindungsfunktionsstufen-0-1.html, accessed 23.09.2021

[63] Kraftfahrt-Bundesamt Güterbeförderung 2020, https://www.kba.de/DE/Statistik/Kraftverkehr/deutscherLastkraftfahrzeuge/vd_Gueterbefoerderung/vd_gueterbefoerderung_node.html, accessed 23.09.2021

[64] Genesis Destatis Table 46131-0013, available at https://www-genesis.destatis.de/genesis/online

[65] Genesis Destatis Table 46131-0007, available at https://www-genesis.destatis.de/genesis/online

[66] Genesis Destatis Table 46321-0005, available at https://www-genesis.destatis.de/genesis/online

[67] Genesis Destatis Table 46321-0008, available at https://www-genesis.destatis.de/genesis/online

[68] Genesis Destatis Table 46321-0012, available at https://www-genesis.destatis.de/genesis/online

4.5 Pipelines

4.5.1 Natural Gas

Current Status

A European-wide pipeline network for natural gas exists, with a dense network in the Rheinisches Revier and Ruhr area. Many connection points to the Belgium and Netherland gas pipeline network are on the borders of NRW. An intra-country balancing zone interconnection point is located in the Rheinisches Revier in Broichweiden (close to Würselen, Aachen), which connects pipelines from the Netherlands, Belgium and the Ruhr area (Düsseldorf, Essen, Dortmund). Further points of intersection are in Paffrath (close to Bergisch-Gladbach) and Werne (close to Hamm). A new pipeline north-west of to the Ruhr area is planned between Haanrade and Winterswijk (both on the border to the Netherlands).[69,70]

Natural Gas - Future Development

The gas pipeline operators propose future network capacity expansion for the years 2020 to 2030 in the "Netzentwicklungsplan Gas" based on two gas demand scenarios for Germany.[71] Two new natural gas pipelines (High caloric –H) are suggested by the operators in the Rheinisches Revier (west of Cologne/Bonn). A mix of hydrogen or synthetic methane is also considered. Until 2030, a hydrogen demand of ca. 3000 MWh/h was deduced from queries of partners. Thus, additional pipelines for "green gas" (+H2 or + synthetic methane) are planned, mainly by using existing natural gas pipelines for green gas (1,142 km for 2030). In addition, 94 km of new hydrogen pipelines need to be built until 2030.

4.5.2 Hydrogen

Current Status

Currently Air Liquide operates the longest hydrogen pipeline network in Europe at the chemical park Marl as the origin with a length of 240 km. The pipeline connects Marl to Castrop-Rauxel and to Leverkusen via Bottrop, Duisburg and Düsseldorf.[23,72]

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[69] The European Network of Transmission System Operators for Gas (ENTSOG) provides a Gas grid map for Europe, including also LNG terminals. https://www.entsog.eu/maps, accessed 23.09.2021

[70] https://www.bmwi.de/Redaktion/DE/Artikel/Energie/gas-erdgasversorgung-in-deutschland.html, accessed 23.09.2021

[71] Proposed infrastructure by FNB-Gas https://www.fnb-gas.de/media/fnb_gas_2020_nep_entwurf_de_kf.pdf, accessed 23.09.2021

[72] EnergieAgentur.NRW, https://broschuerenservice.nrw.de/energieagentur/shop/Hydrogen_%E2%80%93_the_key_to_the_energy_transition/1, accessed 22.09.2021

Hydrogen - Future Development

A 5,900 km long pipeline between Lingen and Gelsenkirchen is planned by the initiative GET H2. Wind parks will produce electricity to operate an electrolyzer with a planned power of 100 MW at the RWE power plant in Lingen to cover the hydrogen demand in NRW, especially of the chemical park Marl. The pipeline is mainly a natural gas pipeline operated by Nowega and OGE, which will be switched to H_2 pipeline. Operation is planned for 2023.[73] In addition, new hydrogen pipelines are planned northern to the Ruhr area connecting Dorsten to Xanten. Furthermore, at the North-West border to the Netherlands several natural gas pipelines are suggested to be switched to hydrogen use.[71]

4.5.3 Other Carbon-based Commodities

Ethylene pipelines lead from Wesseling through the Rheinisches Revier to the Netherlands and from Wesseling to Marl.[23]

Propylene pipelines are available between Cologne, Duisburg, and Marl.[23]

The company N.V. Rotterdam Rijn Pijpleiding Maatschappij (RRP) operates crude oil pipelines in the Netherlands and in Germany. The pipeline starts at Rotterdam and serves the docks at Botlek, Europoort, and Maasvlakte. The crude oil is pumped to Venlo, where a big tank farm exists. From Venlo one branch supplies the Ruhr Oel Refinery at Gelsenkirchen and the other branch supplies the two Rhineland refineries Godorf and Wesseling in Cologne.[74] Further crude oil pipelines are provided by NWO Nord-West Oelleitung GmbH. The pipeline starts at the port of Wilhelmshaven and supplies the Ruhr Oel Refinery at Gelsenkirchen, and the Rhineland refineries Wesseling with crude oil.[75] Along the pipeline at Ochtrup (district of Steinfurt) is a crude oil tank for 50,000 m³.

A pipeline for mineral oil products leads from at Venlo through Ruhr-Area, Rhine, Cologne, Eifel, Frankfurt (Airport) down to Ludwigshafen (BASF). The pipeline is also connected to Rotterdam pipeline (RRP) and supplies the Rhineland refineries Godorf, Wesseling and the refineries in Dormagen and Bottrop. The pipeline belongs to Shell, BP and Exxon Mobil (63, 35 and 2%).[76,77]

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[73] GET H2 Nukleus, https://www.get-h2.de/wp-content/uploads/geth2-nukleus_praesentation_en_210204.pdf, accessed 22.09.2021

[74] RRP N.V., www.rrpweb.nl, accessed 22.09.2021

[75] NWO, www.nwowhv.de, accessed 22.09.2021

[76] Mineralölwirtschaftsverband e.V., www.mwv.de, accessed 22.09.2021

[77] RMR, https://rmr-gmbh.de/wp-content/uploads/2019/05/rmr_einblicke.pdf, accessed 22.09.2021

4.5.4 Overview of the Pipeline Grid

The following map in Figure 4-13 shows the beforementioned pipelines across NRW with a focus on the Rheinisches Revier. Due to visibility, natural gas pipelines are not depicted. It is obvious, that while the chemical parks along the rivers Rhine and Ruhr are well connected, pipelines are missing through the Rheinisches Revier.

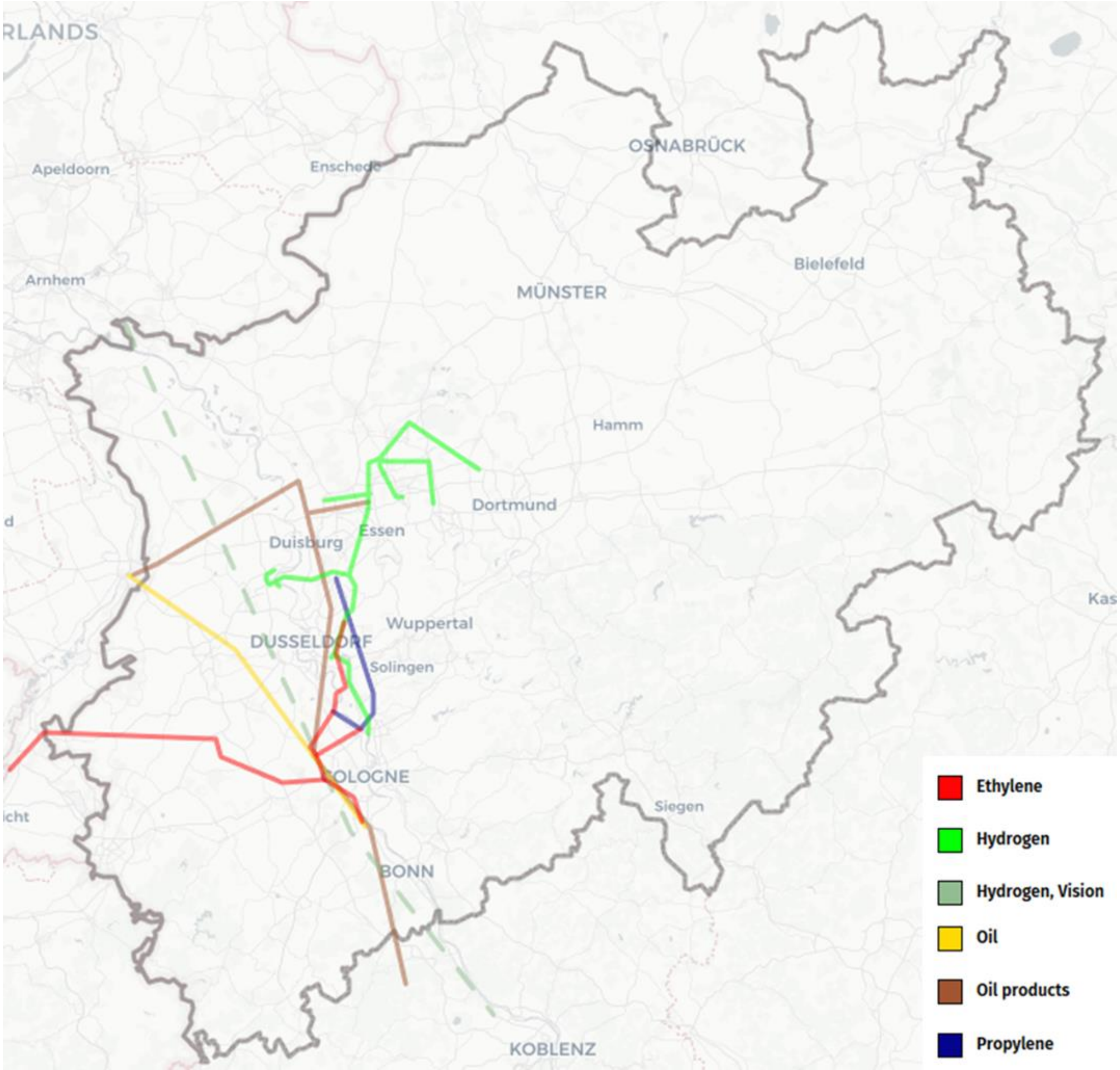

Figure 4-13: Representation of present pipelines in NRW. The hydrogen vision pipeline is a proposal by the gas pipeline operators.[20,23,71,76]

4.6 Agriculture

Nearly half of NRW is used as agricultural land (1.45 Million ha). This agricultural land consists of 72% farmland, 27% grassland and only 1% for permanent crops. Based on area used, growing grains is the largest contributor (0.6 Million ha), followed by corn (0.2 ha). Aside of grain, vegetables and potatoes bear high importance in the agriculture.[78]

4.6.1 Agricultural Land Used for Crops and Livestock

Several crops are cultivated throughout NRW, Figure 4-14 shows the core products in NRW, which are grain (49.7%), maize (27.6%), winter oilseed rape (5.7%), potatoes (3%), sugar beet (4.7%), vegetables/asparagus/strawberries/flowers (2.8%) and other crops (6.7%).[79]

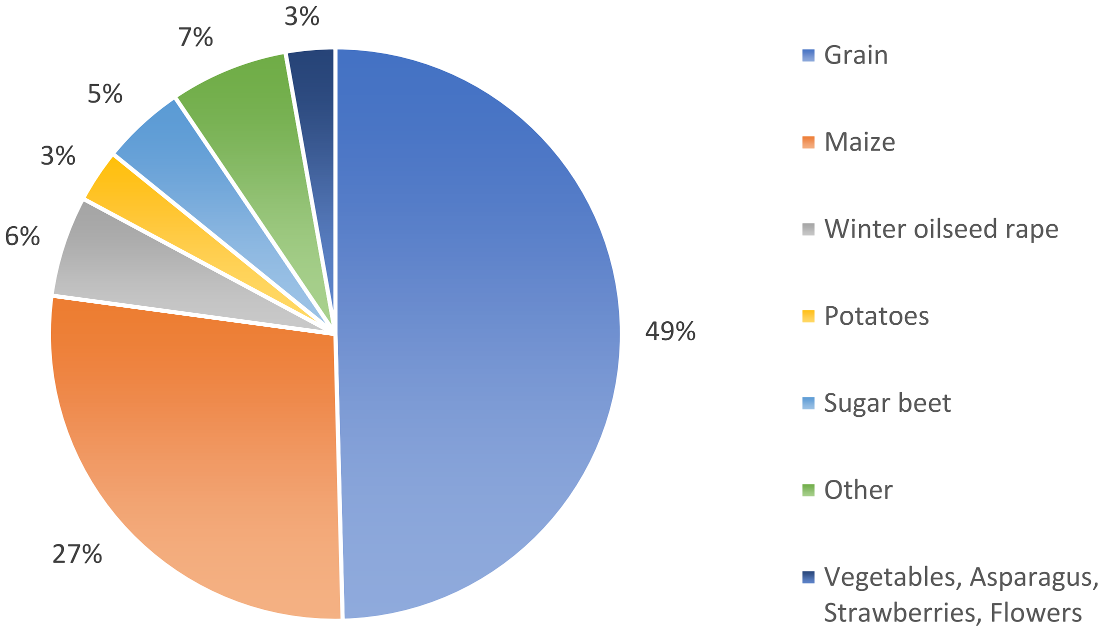

Figure 4-14 Distribution of the agricultural land use in NRW (2016).[79]

The distribution and intensity of utilized agricultural land is shown on the following map, about 2,500 km^2 of land is used agriculturally in the Rheinisches Revier.[80]

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[78] https://www.umwelt.nrw.de/landwirtschaft/acker-und-gartenbau, accessed 23.09.2021

[79] https://www.landwirtschaftskammer.de/wir/pdf/agriculture-in-nrw.pdf, accessed 22.09.2021

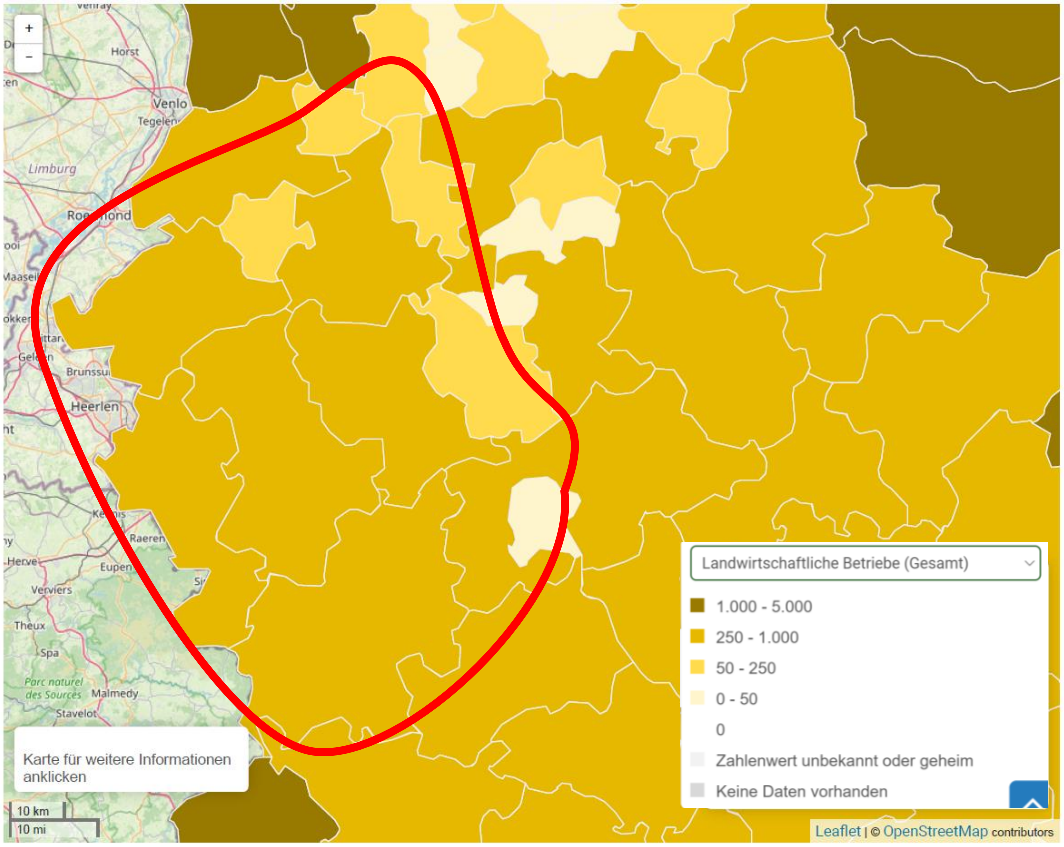

Figure 4-15 Distribution of agricultural land in 2016[80], Rheinisches Revier marked in red.

Outdoor vegetables were cultivated on 26,850 ha in NRW in 2017 producing about 810 kt of vegetables (Germany: 130,153 ha in 2017). Only 1-2% are grown in greenhouses (Germany: 1,200 ha). The self-sufficiency in vegetable supply is only 35% (2015/2016). There are two major agricultural areas for vegetables in North Rhine-Westphalia: Bornheim and Straelen.[81]

Besides the cultivation of land livestock farming plays an important role in NRW. The livestock in 2016 consisted of pigs (7,263,582), cattle (1,412,681), sheep (159,409), horses/donkeys/goats (82,787), fowls/chicken (11,779,163), geese (60,019), ducks (166,745) and turkeys (1,554,480).[82]

The distribution of animal husbandry is shown in the following map, indicating a moderate amount of livestock farming in the Rheinisches Revier and more intense livestock farming in the northern and southern part of NRW.

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[80] https://www.proplanta.de/karten/, Quellen: Statistische Daten des Bundes und der Länder, © GeoBasis-DE / BKG (2020), Leaflet, accessed 23.09.2021

[81] http://www.hortipendium.de/Gem%C3%BCsebau_in_Deutschland#Gem.C3.BCse_Anbaugebiete_in_Deutschland, accessed 23.09.2021

[82] Statistische Berichte Viehhaltungen und Viehbestände in Nordrhein-Westfalen am 1. März 2016, www.it.nrw.de, Bestellnummer C333 2016 51, (Kennziffer C III – 3j/16), accessed 23.09.2021

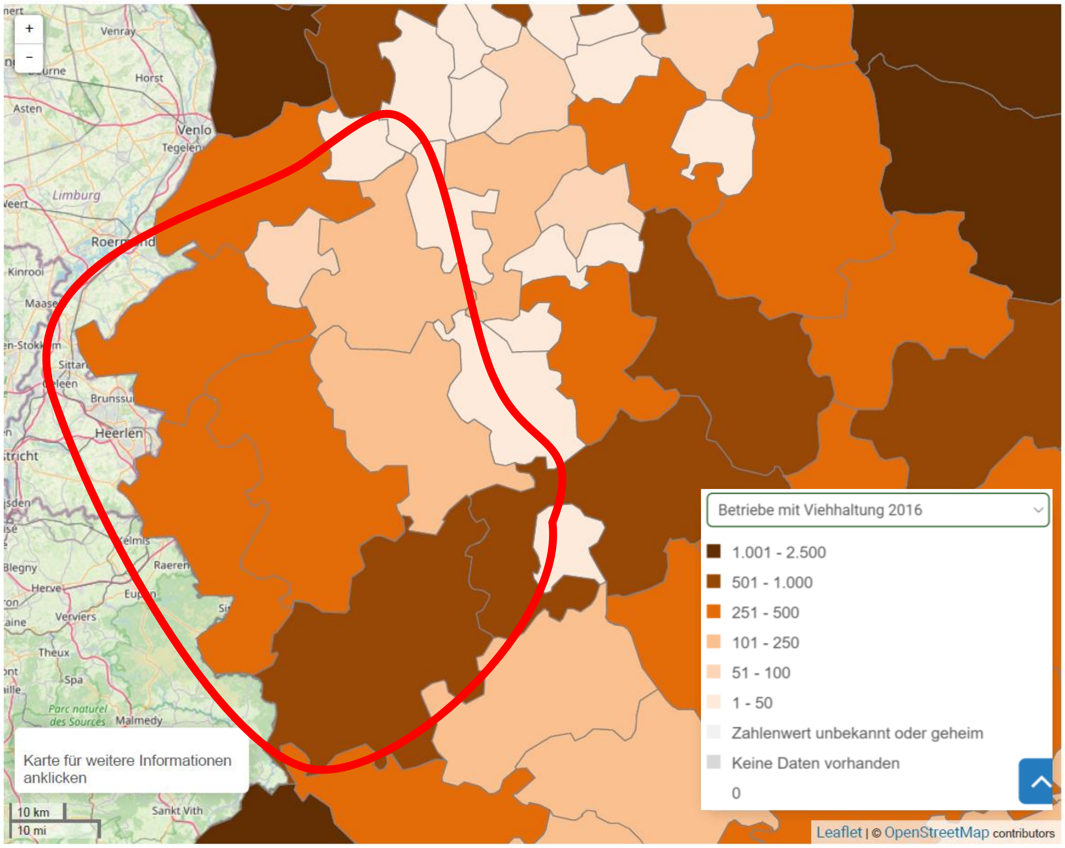

Figure 4-16 Distribution of animal husbandry in western Germany[80], Rheinisches Revier marked in red[80].

Solid forage production is vital to sustain this amount of livestock. Nearly 4 million tons of animal feed are produced in NRW per year, consisting of local produced and imported components. The state NRW is the second biggest forage producer in Germany. Over 40,000 companies are involved in the forage production in NRW.[83]

The Rheinisches Revier is first and foremost strong in the production of grain, vegetables and sugar beet. Particularly the processing of the sugar beet is an essential industry in the Rheinisches Revier. The processing leads to byproducts such as raw sugar molasses, which are used for the production of yeast and penicillin.[84]

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[83] https://www.umwelt.nrw.de/landwirtschaft/tierhaltung-und-tierschutz/nutztierhaltung/futtermittel, accessed 23.09.2021

[84] https://www.rheinisches-revier.de/media/prognos_studie_biooekonomie_potenziale_rhein_revier_rohstoffe_u_ernaehrung_final.pdf, accessed 28.09.2021

Innovation in Agriculture

Innovation in agriculture is an important topic in NRW. There are several projects ongoing, especially in the Rheinisches Revier. The incentive for this innovation-campaign is mostly to handle the structural change, caused by the coal exit plans and the following energy transition.

Bioökonomie Revier is an innovation hub to support the structural change in this area.[85] Its goal is to accelerate the innovation process in the Rheinisches Revier. The projects are distinguished into three approaches:

- **Platforms** (development of ideas and technology)
- **Concepts** (innovation that may be feasible)
- **Qualification** (concepts that are feasible and may be commercialized)

While there are many project ideas, a few deal with similar aspects as some CCU technologies considered in the present study. These projects do not consider CO_2 as a raw material for their process but investigate recycling options to reduce the use of fossil feedstocks and the potential of biotechnology within different applications for biomass or functional biomass production.

- **Platforms**
  - Plastic management
- **Concepts**
  - Upcycling residual material (UpRePP)
  - Extraction of Nutrition from wastewater. Development and construction of two pilots (AlgaeSolarBoxes) (development of a concept for usage of algae as a biomass)
  - Decentralized modular biorefinery container (DeMoBio) (Biomass energy, chemical)
- **Qualifications**
  - Microbial production of pharmaceutical peptides (SenseUp_Prot)
  - Customized protein production to reduce fungicides (ProtLab)
  - Electro hybrid Separation (E-HyBio)

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[85] https://www.biooekonomierevier.de/Innovative_Landwirtschaft, accessed 23.09.2021

4.6.2 Biodiesel

In 2018, Germany produced 3.2 million tons Biodiesel. The most important feedstock was rapeseed (57.8%). Other feedstocks were: soybean oil (8.4%), palm oil (2.3%), used cooking fat (27%), animal fats (2.1%), fatty acids (2.0%) and other (0.4%). Biodiesel production is located throughout Germany, details are shown in Table 4-2. Biodiesel plants in NRW are located in Neuss, Lünen and Borken.[86]

Table 4-2 Biodiesel plants and production capacities reported for 2018 in Germany.[86]

Operator / Plant	Location	Capacity (t/year)
ADM Hamburg AG – Hamburg plant	Hamburg	Not available
ADM Mainz GmbH	Mainz	Not available
Bioeton Kyritz GmbH	Kyritz	80,000
BIO-Diesel Wittenberge GmbH	Wittenberge	120,000
BIOPETROL ROSTOCK GmbH	Rostock	200,000
Biowerk Sohland GmbH	Sohland	80,000
Bunge Deutschland GmbH	Mannheim	100,000
Cargill GmbH	Frankfurt/Main	300,000
ecoMotion GmbH	Sternberg	100,000
ecoMotion GmbH	Lünen	162,000
ecoMotion GmbH	Malchin	10,000
German biofuels gmbh	Falkenhagen	130,000
Glencore Magdeburg GmbH	Magdeburg	64,000
Gulf Biodiesel Halle GmbH	Halle	56,000
KFS Biodiesel GmbH	Cloppenburg	50,000
KFS Biodiesel GmbH	Niederkassel-Lülsdorf	120,000
KFS Biodiesel GmbH	Kassel/Kaufungen	50,000
Louis Dreyfus Commodities Wittenberg GmbH	Lutherstadt Wittenberg	200,000
Mercuria Biofuels Brunsbüttel GmbH	Brunsbüttel	250,000
NEW Natural Energie West GmbH	Neuss	260,000
Rapsol GmbH	Lübz	6,000
REG Germany AG	Borken	85,000
REG Germany AG	Emden	100,000
TECOSOL GmbH	Ochsenfurt	75,000
Verbio Diesel Bitterfeld GmbH & Co. KG (MUW)	Greppin	190,000
Verbio Diesel Bitterfeld GmbH & Co. KG (NUW)	Schwedt	250,000
Total		**3,038,000**

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[86] https://www.ufop.de/files/7215/7112/3444/ENG_UFOP_1693_Biodieselauszug_2019_151019.pdf, accessed 23.09.2021

4.6.3 Bioethanol

According to the BDB^e – Bundesverband der deutschen Bioethanolwirtschaft e.V. –Bioethanol production is mainly located in Brandenburg, Mecklenburg-Vorpommern, Sachsen-Anhalt and Bayern.[87] There are currently no bioethanol plants in NRW reported by BDB^e. The combined production volume in 2019 was 651,565 tons bioethanol, which is a reduction of 13.5% compared to 2018. Hence, less bioethanol was available for chemical and pharmaceutical industry and for blending into gasoline. 86% of the German bioethanol was produced from feed grain and 14% from sugar beet. A very small part was produced by waste product.

The demand of bioethanol in Germany exceeds the local production. In 2019 about 1.16 million tons of bioethanol was blended into gasoline, which was a reduction of 2% compared with the previous year. The bioethanol quota in the German gasoline types Super Plus, Super (E5), Super (E10) and in ETBE was 6.1% in 2019 compared to 6.3% in 2018, which is still in line with the minimum quota of 6.0%.[87]

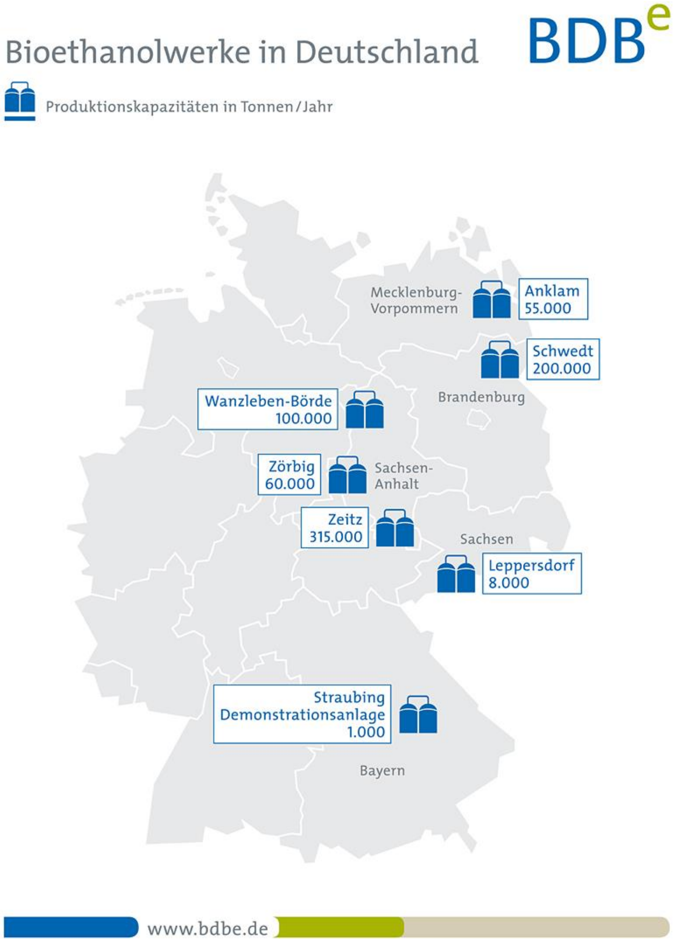

Figure 4-17 Bioethanol plants in Germany – production capacity in tons/year[88], illustration from BDB^e.

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[87] https://www.bdbe.de/application/files/8515/8746/4313/Marktdaten_2019_1.217_2020_04_03.pdf, accessed 23.09.2021

[88] https://www.bdbe.de/wirtschaft/mitglieder, accessed 23.09.2021

4.7 Representation in a Map

The infrastructure analyzed in previous sections is collected and main components are inserted in a map to enable a visual representation. The figure below shows the CO_2-emitting industry in NRW, pipelines relevant for the utilization of CO_2 and the region Rheinisches Revier. The industrial facilities are shown as dots whereas the infrastructure is drawn as lines. The dashed green line represents a proposed hydrogen pipeline for future implementation.

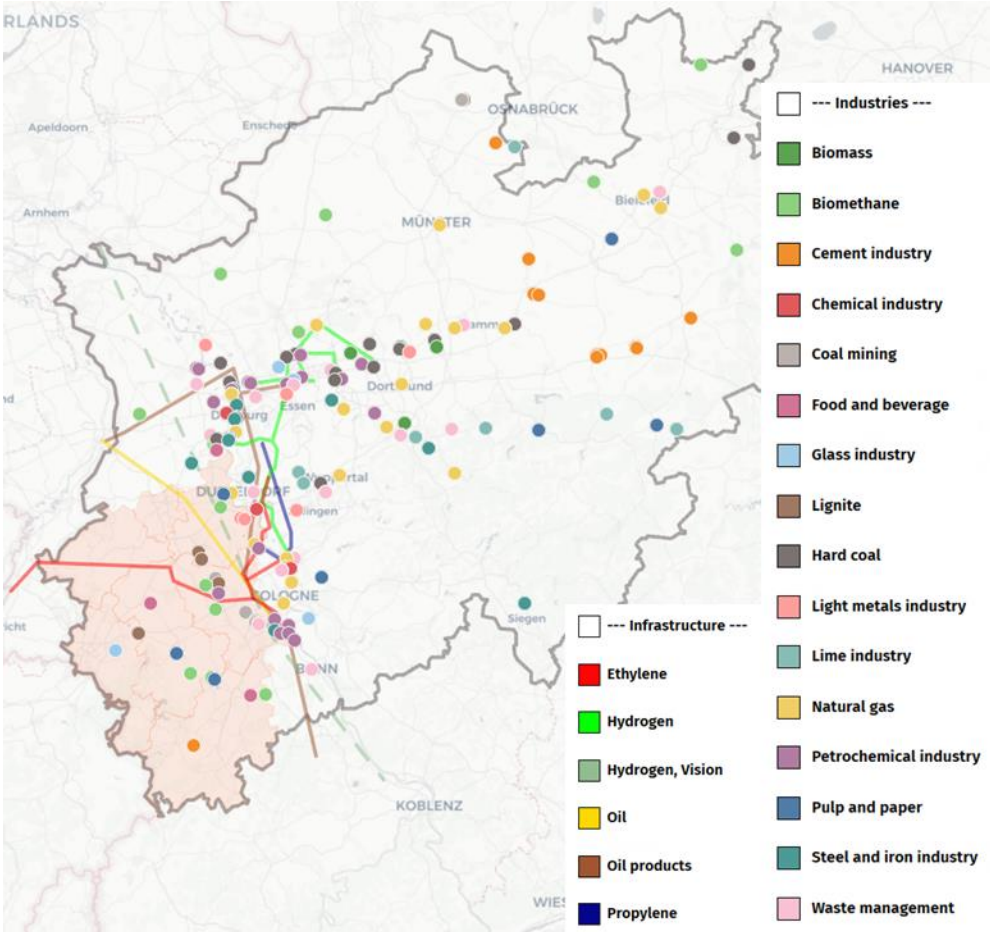

Figure 4-18: Representation in a map of the CO_2-emitting industry in NRW, relevant infrastructure and the Rheinisches Revier.[19,20,23,46,76]

Taking a closer look at the Rheinisches Revier, it can be seen that most of the pipelines transporting essential components for chemical processes connect the Cologne area with Düsseldorf, Duisburg and Essen. The only pipeline passing not only the border but located also in the core of the region is the Ethylene pipeline (red). It can also be seen that a first suggestion for a prospective hydrogen pipeline (dashed, green) would also only pass the core region at its outer parts.

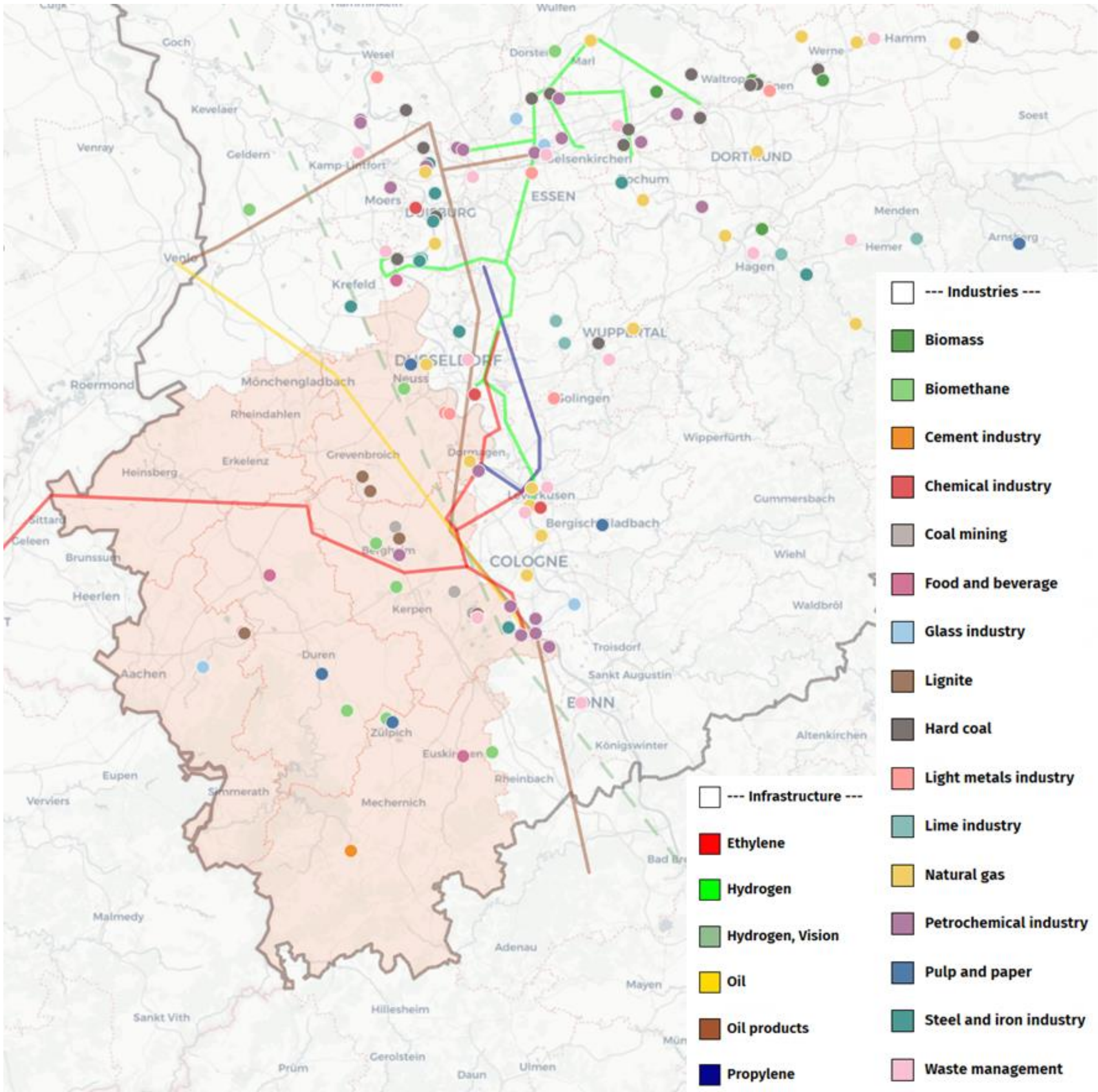

Figure 4-19: Representation in a map of the CO_2-emitting industry in Rheinisches Revier and relevant infrastructure.[19,20,23,46,76]

5 Part B: CCU Idea Ranking

The second part of the study establishes a basis for the comparison of possible CCU ideas and selects suitable options. First, appropriate criteria and scorings are defined. This is followed by an assessment of CO_2 supply options and the social acceptance. Afterwards the criteria are weighted and applied to the collected list of chemicals, fuels and proteins/biomass. Each product section is discussed and suitable ideas for NRW are determined.

5.1 Criteria Catalogue and Scoring Guide

The criteria to compare the different processes are collected through a literature review and internal discussions. For the ranking of CCU ideas a procedure similar to the study of Chauvy et al.[89] was followed. However, the selection of processes and criteria was significantly extended. As a result, a separation in five groups was derived, considering following aspects: Technical, Infrastructure, Environmental compatibility, Economic feasibility and Rollout scenario.

In total, 21 sub-criteria were employed in these groups, which are shown in the following tables. The scope of the sub-criteria covers a wide range from purely technical aspects such as time to market, to carbon footprints and employment effects. The table also contains the scoring guide and explains the parameters used. In cases where no absolute reference points were available for the scoring – for example economic and rollout assessment – percentiles were used.

Initially the scoring was performed with an ideal energy demand of the reactions, considering only the reaction enthalpy. In a second step, these demands were increased to those of the real process conditions, where information was available. In case of missing information, a surplus energy demand was attributed to the processes, especially to consider realistic consumptions of exothermic reactions, which would be otherwise net energy producers.

Table 5-1: Criteria list for comparison of process ideas: technical.

Criteria	Sub-criteria	Explanation	Parameter		Score
Technical	**Time to market**	Development status for deployment. Based on the TRL definitions of the GlobalCO₂Inititative. The processes are divided in five groups: purely technical, pilot in planning, pilot in operation, demo in operation and already commercial.	TRL	1-3	0
			TRL	4-5	1
			TRL	6	2
			TRL	7-8	3
			TRL	9	4
	Flexibility	Defines if a load-flexible operation is possible to follow the renewable electricity production, such as electrochemical or photochemical processes.	Catalytic, high-temperature or similar process		0
			Electrochemical, biotechnological process		4

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[89] Chauvy et al., 2019, Selecting emerging CO_2 utilization products for short- to mid-term deployment, Applied Energy

Table 5-2: Criteria list for comparison of process ideas: infrastructure.

Criteria	Sub-criteria	Explanation	Parameter	Score
Infrastructure	**CO_2 quality**	Defines if CO_2 has to be pure or can be contaminated. Technologies with catalysts were considered to require pure CO_2.	Catalytic (high purity) Non-catalytic (low purity)	0 4
	Major mass flows	Ranking according to the used major mass flows.	Ethylene oxide, propylene oxide required Additional chemicals (e.g. H_2, CH_4, Methanol) required Only heat, electricity, H_2O and CO_2 required	0 2 4
	Energy demand	Energy demand of the anticipated plant, including the hydrogen production. In the ideal case, the reaction enthalpy is taken as the source for the energy demand. In the real case, process efficiencies were used.	Percentiles	0-4
	NRW production (current)	Defines if a (conventional) production of the respective CCU product is locally existent.	Non-existing Existing	0 4
	CO_2 demand	Ranking according to utilized quantity, resulting in transport by road, rail or pipeline.	Above 200 kt/a (pipeline) Above 8 kt/a (railway) Below 8 kt/a (road transport, 1 time/week)	0 2 4

Table 5-3: Criteria list for comparison of process ideas: environmental compatibility.

Criteria	Sub-criteria	Explanation	Parameter	Score
Environmental compatibility	**CO_2 fixation (theoretic)**	CO_2 fixed in product, stoichiometric.	Percentiles	0-4
	Carbon footprint (current)	CO_2 GWP including direct and indirect emissions (due to energy demand) of the process with current conditions.	If value is negative Percentiles if positive	0 1-4
	Carbon footprint (future)	CO_2 GWP including direct and indirect emissions (due to energy demand) of the process with future conditions.	If value is negative Percentiles if positive	0 1-4
	Toxicity	Toxicity of by-products and raw materials compared to the conventional process.	Worse than convent. process No difference or not quantifiable Better than convent. process	0 2 4

Table 5-4: Criteria list for comparison of process ideas: economic feasibility.

Criteria	Sub-criteria	Explanation	Parameter	Score
Economic feasibility	**Business case**	Economic viability based on the relative added value: $\frac{\text{Market price} - \text{varOPEX}}{\text{varOPEX}}$	Percentiles	0-4
	CO_2 fixation costs	CO_2 price required to break even with conventional product: $\frac{\text{Market price} - \text{varOPEX}}{\text{kg } CO_2 \text{ in product}}$	Percentiles if negative Positive value	0-3 4
	Competitiveness with other technologies	TRL comparison with alternative, sustainable pathways.	Lower TRL than bio-based route Same TRL as bio-based route Higher TRL than bio-based route	0 2 4
	End markets	Ranking of products according to their number of market applications. In total, 18 markets were considered.	Percentiles	0-4

Table 5-5: Criteria list for comparison of process ideas: rollout scenario.

Criteria	Sub-criteria	Explanation	Parameter	Score
Rollout scenario	**Market size**	Ranking according to European market size in t/a.	Percentiles	0-4
	Market value	Ranking according to European market value in EUR/a.	Percentiles	0-4
	Market growth	Ranking according to European market volume growth (CAGR) in %/a.	Percentiles	0-4
	Rollout potential	Describes the number of plants, which could be built in NRW according to NRW share of current German chemical industry.	Percentiles	0-4
	Rollout potential, export	Describes the number of plants, which could be exported aiming for 10% share of current global chemical industry.	Percentiles	0-4
	Employment effects	Describes the effect on direct jobs created by the process.	Percentiles	0-4

A comparative life cycle assessment (LCA) yields the reduction potential of CO_2-eq and the effect on toxicity for each CCU process. The conventional process and background data are based on the ecoinvent 3.5 data base (cutoff version). The aim of the LCA is to identify the reduction potential by comparing the conventional production process to the CCU process with the focus on the impact categories: Climate change and human toxicity (carcinogenic and non-carcinogenic) using the ILCD Midpoint method[90]. The system boundaries are defined according to the cradle-to-gate approach with 1 kg of product as functional unit. Two scenarios highlight the effect of selecting different sources for CO_2, H_2, electricity and heat supply on the climate change and toxicity impact for both the CCU and conventional process. The resulting carbon footprint of the selected material and energy sources for the two scenarios is depicted in Figure 5-1 (green: green future scenario; grey: current scenario).

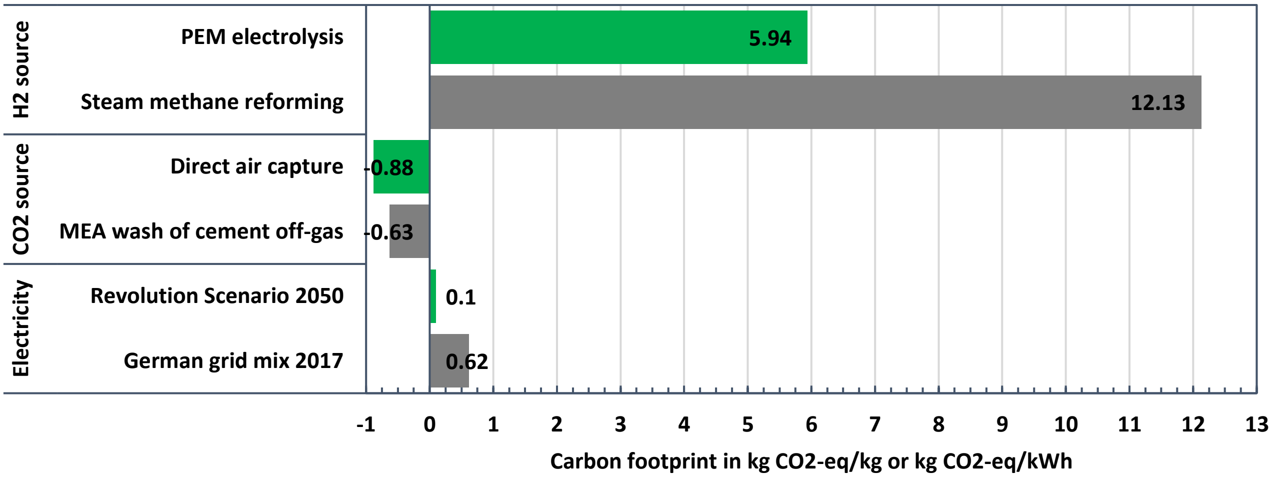

Figure 5-1: Depiction of the current scenario (gray), and green future scenario (green) regarding the assumed hydrogen, CO2 and electricity source.

The "current" scenario describes the production with current state-of-the-art boundary conditions, i.e., H_2 via steam methane reforming[91], CO_2 capture with amine-scrubbing from cement plant off-gas[92], German electricity mix at medium voltage[93], and heat provided by a market mix of natural gas, oil, coal and biogas in case of conventional plants or covered with electricity in case of the CCU option[93]. In contrast, the "green Future" scenario applies boundary conditions, which promise lower greenhouse gas emissions: H_2 from PEM electrolyzer[94], CO_2 by direct air capture[95], an electricity mix according to the "revolution scenario" for 2050 by EWI study[96], and heat supplied by electricity. The assumed electricity

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[90] European Commission - Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; 2010

[91] Mehmet et al., 2018, Life cycle assessment and water footprint of hydrogen production methods: from conventional to emerging technologies, environments

[92] Müller et al., 2020, The carbon footprint of the carbon feedstock CO_2, Energy & Environmental Science

[93] ecoinvent 3.7 cutoff, market mix electricity at medium voltage based on year 2017

[94] Bareiß et al., 2019, Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems, Applied Energy. Assumptions: LCI is based on future material and energy demand of PEM. Electricity supply via Revolution Scenario for 2050.

[95] Deutz et al., 2021, Life-cycle assessment of an industrial direct air capture process based on temperature–vacuum swing adsorption, Nature Energy. Assumptions: future scenario with "Global 2050" as energy supply scenario and heat from a heat pump.

[96] EWI - Energy Research & Scenarios gGmbh, 2018, The energy market in 2030 and 2050 – The contribution of gas and heat infrastructure to efficient carbon emission reductions.

mix is composed of wind power (59%) and PV (22%), but also gas power (10%) as depicted in Figure 5-2 in comparison to the German grid mix for 2017 at medium voltage.

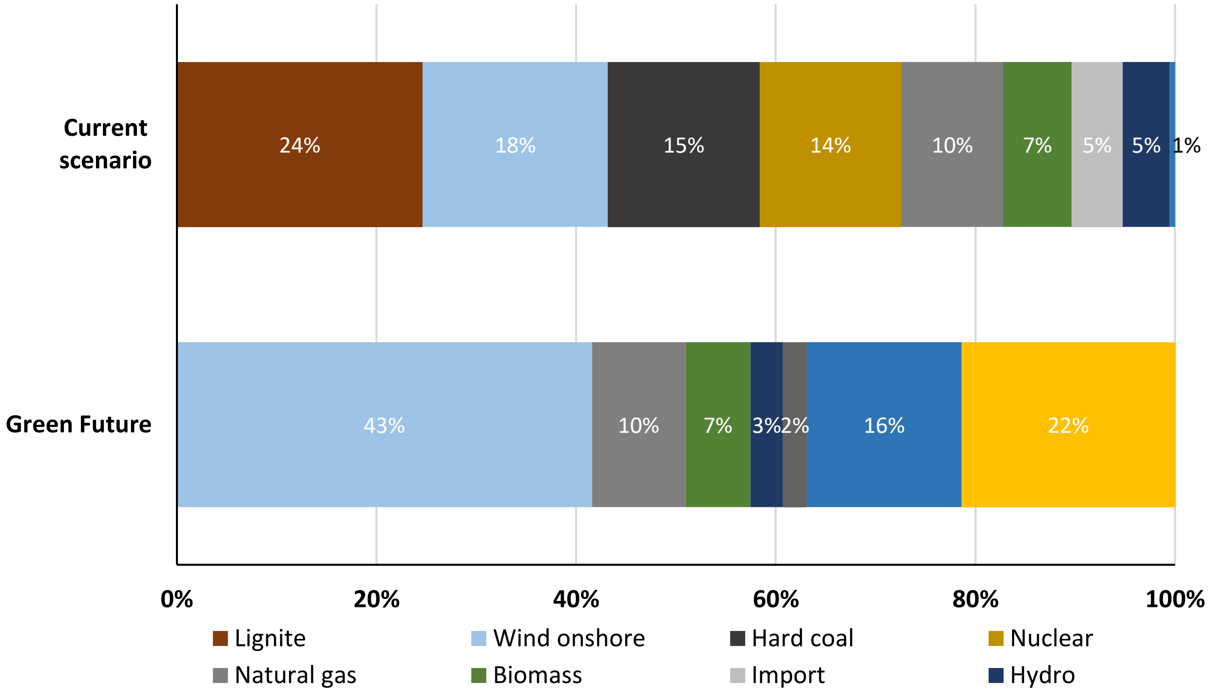

Figure 5-2: Share of electrical sources in net energy production for current scenario (German electricity grid mix at medium voltage for 2017 based on ecoinvent[93]) and for green future scenario (based on Revolution Scenario for 2050[96]).

5.2 CO₂ Supply

The capture of CO_2 from point sources or from the atmosphere can be divided into these approaches: three for point sources with pre-combustion capture, oxyfuel combustion, post-combustion capture and one for atmospheric capture with direct air capture (DAC). For CCU post-combustion capture plays a crucial role to extract CO_2 from point sources as it can be retrofitted to a plant and DAC to capture the CO_2 of widely distributed sources, e.g., of cars or airplanes combusting (synthetic) fuel. Post-combustion capture removes CO_2 from flue gases via cryogenic, membrane, adsorption or absorption processes.

In chemical or physical absorption processes the CO_2 reacts with a chemical solvent, commonly amine-based since it is the most cost effective and mature technology.[97] This step is performed after removing nitrogen oxides and sulphur oxides of the flue gas to prevent any reaction with the solvent. Chemical absorption has the advantage of high removal efficiencies of around 95% and its applicability for low concentration of CO_2 in the flue gas.[98] However, one drawback of absorption-based capture using amines is the high energy requirement for the solvent recovery, which results in high parasitic consumption and thus high costs (70–80% of the total operating cost of the system).[99]

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[97] Koytsoumpa et al., 2018, The CO2 economy: Review of CO2 capture and reuse technologies, The Journal of Supercritical Fluids

[98] Karakas et al., 2012, Pressurized fluidized bed combustion (PFBC) combined cycle systems, Combined Cycle Systems for Near-Zero Emission Power Generation

[99] Mondal et al., 2012, Progress and trends in CO2 capture/separation technologies: A review, Energy

The adsorption of CO_2 makes use of significant intermolecular forces between the CO_2 and the surface of certain solids in the form of molecular sieves or activated carbon. The adsorbent can be regenerated by either increasing the temperature (temperature swing adsorption), or by decreasing the pressure (pressure swing adsorption). Due to large cycle times, the temperature swing adsorption method is limited to small applications, whereas pressure swing adsorption allows rapid cycling. In addition, pressure swing adsorption requires less heat which lowers its cost.[99] However, this approach reacts sensitive to water presence or impurities in the flue gas.[99]

Cryogenic capture of CO_2 is only applied for CO_2 flows with high concentrations (> 50%), because of its significant energy requirement. It produces liquid CO_2, which is beneficial for an economic transportation and runs at atmospheric pressure. However, cryogenic capture is susceptible to H_2O, SO_x and NO_x impurities in the flue gas.[99]

In contrast to the mature cryogenic capture, membrane technology is a novel concept. It is based on selective membranes to separate CO_2 from the feed gas. These semi permeable barriers separate due to either diffusion mechanism, by acting as a molecular sieve or by ionic transport.[99] So far, merely a low removal efficiency and low purity of CO_2 could be achieved.[100] In addition, this method is only feasible for CO_2 concentrations above 20%.[101]

Not all of these described CO_2 capture methods are equally advisable for a specific industry sector. For example, the amine-based absorption approach is suggested for the cement industry due to its removal efficiency of more than 80%.[102] However, the cement plant can provide only less than 50% of the required heat for solvent regeneration. A second option is the calcium looping capture for CO_2 from cement plants, since it is based on limestone as raw material and could feature lower energy penalties than absorption capture.[103] The project "CLEANKER" is an ongoing Horizon2020 funded EU project to further develop the integration of the calcium-looping process into the production process of a cement plant at pilot scale[104]. For the steel and iron industry the pressure swing adsorption is advisable for oxygen blast furnaces or top recycling blast furnaces.[103] In case of common blast furnaces, the SO_x, NO_x and dust in the flue gas needs to be removed beforehand. Refineries with their scattered emission points would benefit from a pipeline network leading to a centralized capture unit, e.g. via amine absorption.[103] In the power sector, mono ethanol amine (MEA) capture is widely applied since it is mature and commercially available. The MEA-based capture process usually adds an efficiency penalty of 6–14% on coal or combined cycle gas power plants.[105]

Next to technological and economic feasibility aspects of capturing CO_2 from point sources of specific industry sectors, its environmental benefit should be considered. By comparing the carbon footprints of different CO_2 point sources, the industry sector which reduces CO_2-eq emissions most effectively can be

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[100] Olajire, 2010, CO2 capture and separation technologies for end-of-pipe applications – A review, Energy

[101] Brunetti et al., 2010, Membrane technologies for CO2 separation, Journal of Membrane Science

[102] Kuramochi et al., 2012, Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes, Progress in Energy and Combustion Science

[103] Romano et al., 2013, Application of Advanced Technologies for CO2 Capture From Industrial Sources, Energy Procedia

[104] http://www.cleanker.eu/, accessed 17.09.2021

[105] Cebrucean et al., 2014, CO2 capture and storage from fossil fuel power plants, Energy Procedia

identified. This carbon footprint indicates the reduction of greenhouse gas emissions due to the capture in comparison to the conventional process. Thus, negative carbon footprints of the CO_2 capture from point sources do not refer to a physical CO_2 sink for the atmosphere, but rather depict the reduction potential when switching from a conventional CO_2 emitting process to the same process including a capture unit. Thus, the obtained CO_2-eq reduction potentials should be only considered in a time frame, where this upgrading of conventional plants with a carbon capture unit is still an open option. A life-cycle analysis with a cradle-to-gate approach yielded that for today's industry sectors hydrogen plants, ammonia production plants, ethylene oxide production, natural gas processing, and fermentation to ethanol have the lowest carbon footprints of -0.95 kg CO_2-eq/kg CO_2 captured each.[106] Therefore, these point sources should be favored regarding the CO_2-eq emissions when selecting a point source today. Their low carbon footprint can be attributed to a nearly pure CO_2 off-gas stream of these processes, which results in lower energy penalties to capture the CO_2.[107] In case of the hydrogen plant the energy demand was averaged from hydrogen production via steam methane reforming or from coal using either amine or Selexol-based scrubbing to capture CO_2. Next best option of point sources regarding their average carbon footprint is CO_2 captured from pulp and paper mills, waste incineration plants, coal and integrated gasification combined cycle plants, biogas power plants, steel and iron mills and natural gas combined power plants with an average carbon footprint in the range of -0.88 to -0.78 kg CO_2-eq/kg CO_2 captured.[107] Today, the least average CO_2-reduction potential has the direct air capture process (-0.592 kg CO_2-eq/kg CO_2), followed by cement plants (-0.63 kg CO_2-eq/kg CO_2) and refineries and steam cracker (-0.64 kg CO_2-eq/kg CO_2). However, these values are often averages of different capture technologies, e.g. in case of cement plants the capture via post combustion with MEA, KS-1, or advanced solvents is considered, but also oxyfuel kiln and calcium looping with or without heat recovery. In addition, the LCA study assumed that coal covers the energy demand of carbon capture from cement plants to a great extent, whereas the energy demand for carbon capture of coal power plants is only provided by electricity. Thus, the presented value for cement plants can be considered as a worst-case scenario.[93]

For a low carbon economy of a future Europe, it is expected that CO_2 point-sources could be reduced by almost 80% to 330 Mt CO_2/a, which corresponds to the minimum CO_2 feedstock supply.[92] In this scenario fossil fuels are no longer employed and all CO_2 avoidance technologies are applied to their full potential, e.g. only renewable energies for electricity generation, electrode vessels for heat supply, and synthetic methane to meet the fuel demand. Under such ideal assumptions, the average carbon footprint of CO_2 point-sources decreases especially for CO_2 capture from lowly concentrated off-gas to a range of -0.98 to -0.99 kg CO_2-eq/kg CO_2 feedstock.

As the largest CO_2 emitters in NRW - the lignite-fired power plants – will stop their operation until 2038, CO_2 emissions will be reduced and industrial sectors with high process-related CO_2 emissions will be responsible for the highest contribution afterwards. In the context of NRW, the iron and steel industry, the petrochemical industry, and cement industry will play a major role. Thyssenkrupp is currently investigating the use of hydrogen instead of coal in the blast furnace to reduce the carbon footprint of the

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[106] Müller et al. 2020, The carbon footprint of the carbon feedstock CO_2. Royal Society of Chemistry, Energy & Environmental Science

[107] von der Assen et al., 2016, Selecting CO_2 Sources for CO_2 Utilization by Environmental-Merit-Order Curves. Environmental Science & Technology

process[108]. Thus, future CO_2 emissions from the iron and steel industry might be lower than anticipated today. Since cement and lime plants have the highest share of process-related CO_2 emissions of 65%[48], it can be assumed that these plants will be equipped with carbon capture units eventually, as their contribution to NRW's CO_2 emissions will rise in future and CO_2 capture is a decisive factor for a carbon neutral cement industry.[109] Thus cement plants were selected as potential CO_2 point source for the environmental analysis in the "current" scenario. Nevertheless, point sources with a high CO_2 concentration, e.g. from fermentation plants, or pulp and paper mills, should be favored for CCU pilot plants, considering the CO_2 reduction potential.

5.3 Social Acceptance

Social and public acceptance towards new technologies is crucial for its successful implementation. Various topics within industry and energy contexts in the past have shown, how the lack of public awareness and social acceptance have delayed or even prevent new technologies in the roll-out. One well known example here is the "not in my backyard" issue with wind turbine installations while in general renewable energy experiences high acceptance.[110] Another example is the topic Carbon Capture and Storage (CCS), which was intensively researched and developed in the early 2000s in Germany and across Europe. The public concern about the safety and foremost rejection of CO_2 underground storage hindered the roll-out of this technology in Germany. Only recently, the discussion is re-opened with a different focus in respect to applicable CO_2 sources and stronger need for CO_2 mitigation to achieve the climate targets. This change in discussion indicates how the acceptance of a technology (e.g. carbon capture) depends on the application it is applied to: while CCS at fossil power plants experiences low acceptance, because renewable energy is seen as a general solution for energy production, CCS at industrial CO_2 point sources might reach higher acceptance if there is no alternative.

With respect to Carbon Capture and Utilization as a low carbon technology, the relevance of public perception and social acceptance has been recognized early on. Some studies have been undertaken in the past, for example by RWTH Aachen[111] , IASS Potsdam and University of Sheffield[112] to analyze the risk benefit perception and public acceptance of CCU (RWTH) and to review the social acceptance of CCU and required research in this area (IASS / Sheffield).

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[108] https://www.in4climate.nrw/best-practice/projekte/2019/wasserstoff-statt-kohlenstoff-by-thyssenkrupp-steel/, accessed 20.09.2021

[109] Verein Deutscher Zementwerke (VDZ), 2020, Dekarbonisierung von Zement und Beton – Minderungspfade und Handlungsstrategien

[110] https://www.ews-consulting.com/tl_files/media/ews_global/downloads/pdf%20Sonstiges/studie_akzeptanz_wp_muf_frisch_sokic_2018.pdf, accessed 22.09.2021

[111] Arning et al., 2019, Risk-benefit perceptions and public acceptance of Carbon Capture and Utilization, Environmental Innovation and Societal Transitions

[112] Jones et al., 2017, The Social acceptance of Carbon Dioxide Utilisation: A Review and Research Agenda, Front. Energy Res.

Key Results of these studies:

The Human-Computer Interaction Center of the RWTH Aachen performed interviews and online surveys to identify what laypeople already know about CCU and what their current fears regarding CCU are. The doubts of laypeople are generally[113]environmental risks, health risks, quality risks of the CCU products and sustainability risks of products and CCU technologies.[111] The results of the surveys showed a positive attitude towards CCU technologies. The participants indicated a higher need for information on the CCU products than on the corresponding manufacturing company. The main problem of lack of acceptance among the people is that they do not know what CCU is, also because most of the information is not publicly available. Therefore, in order to achieve acceptance of CCU products and their production among the population, it is essential to inform the people about the processes used.

Additional to the "general acceptance", the "local acceptance" must also be considered, if the CCU systems are commissioned in the immediate neighborhood of citizens. In a second study of the RWTH Aachen[111] a survey was launched in which the location of CCU systems was discussed. Local acceptance of CCU site deployment would be tolerated by 56.4%, 16.4% would approve the deployment in their neighborhood, 11% would protest against it. There is a lower acceptance with CCU sites in the surrounding neighborhood than a general acceptance of CCU technology. This relates to the general "not in my backyard" issue.

Impact of Social Acceptance for CCU Study

As a general conclusion the overall view on CCU is positive. Although it is necessary to provide detailed information for laypeople to understand the technical background but it has to be in non-technical language so that everyone can understand the information.

The major factors to impact the social acceptance so far are expected to be more towards infrastructural and technological topics than on a designated CO_2-based product of this CCU study. Most of the discussed CCU options in this study are not final goods, but are used as intermediates. Ultimately, the discussion is about whether CO_2 will be accepted as a sustainable raw material in future.

Therefore, it is not expected that currently a difference in social acceptance of an individual CCU idea discussed in this study could be reasonably identified. However, with the criteria in the section "Infrastructure" and "Rollout" relevant indicators, which are important to the public, are considered in the overall assessment. Higher demand on CO_2 or other feedstock supply comes along with the need for more transport infrastructure, which is considered with a lower scoring than CCU options without the need for additional infrastructure. On the other side, if a CCU pathway potentially generates or maintains employment options in NRW, it is very likely to achieve higher acceptance over time.

Furthermore, with increased discussions on CCU topics, sustainable carbon sources for chemical industry and the transport sector, more information will be available to the public. If this is done properly, the public perception of this topic will change over time and CCU as part of renewable carbon sources might reach the same status like renewable energy in respect to social acceptance.

Until then, dissemination of CCU related activities is crucial to involve and inform the public. Additionally, it might be easier in respect to public acceptance to rather realize CCU demo projects on existing industrial

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[113] Arning et al., 2017, Risk perception and acceptance of CDU consumer products in Germany, Energy Procedia

sites than on green fields as the changes in close proximity to neighborhoods are less. A combination with a site-specific information center / technology center could be beneficial for addressing the people's fears and concerns.

5.4 Weighting of Selected Criteria

A common way to weight the criteria is the cost-utility analysis which divides the weighting based on the experience of the decision makers. A more thorough approach is the analytic hierarchy process (AHP), which was developed by Saaty[114]. It is based on the pair-wise comparison of each criterion inside a group which leads in the end to a hierarchy. Saaty proposed a scale from 1–9, with 1 showing an equal importance and 9 the highest importance compared to the considered criteria. Reciprocal values indicate the opposite importance. The scores were agreed on after discussion, which resulted in the final weightings shown in Figure 5-3.

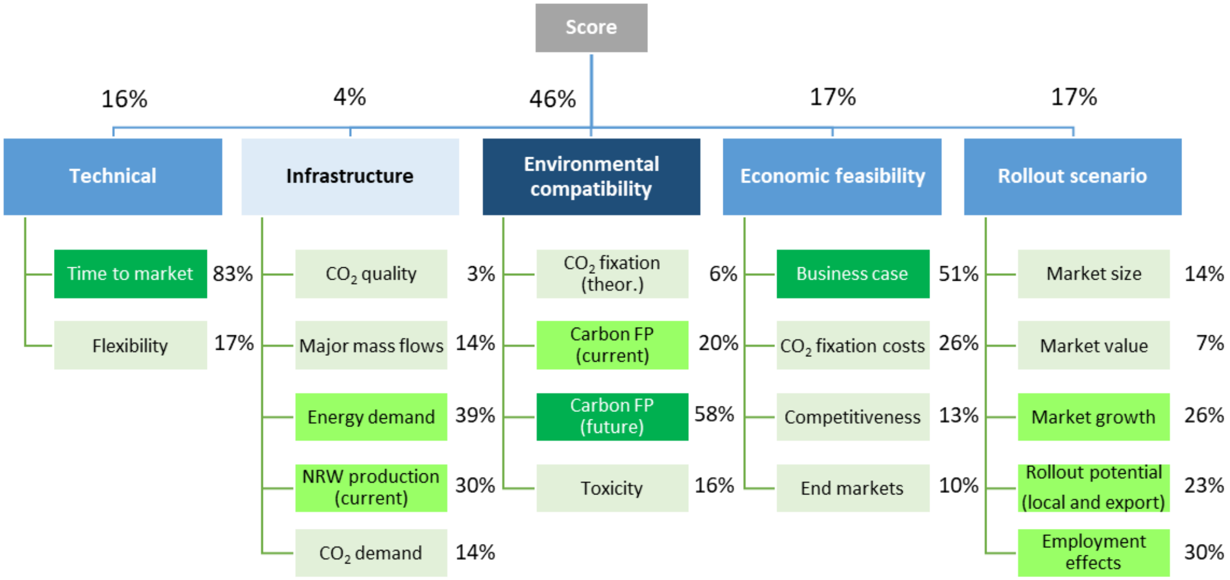

Figure 5-3: Weighting of utilized criteria and sub-criteria determined with the AHP method.

The main driver for the obtained weighting was that the considered processes should be more sustainable than the existing conventional processes. Thus, the highest weighting of 46% was obtained for the criteria "Environmental Compatibility", with the footprint in the future being most decisive. The economic and technical aspects were seen as equally important, achieving ratings of 17% and 16%. In the technical criteria, the TRL was considered as the critical parameter (83%). For the economic feasibility, the business case was found as the most important variable (51%) followed by the CO$_2$ avoidance cost (26%). For the rollout, the market growth, rollout potential and employment effect were valued at a similar level (23–30%).

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[114] Brunelli, 2014, Introduction to the analytic hierarchy process, Springer

5.5 CCU Ideas for NRW

The core purpose of the first phase of the study was to select 2-5 CCU ideas, which have the best fit for the NRW region. Therefore, an initial list was created by literature research and brainstorming. The next step was to filter the ideas and to exclude the ones not being compatible with the selected requirements. The key prerequisite was, that the CCU process is improving the environmental compatibility. This means that CCU ideas, where the conventional process is already bio-based, were excluded. Furthermore, options were excluded, where CO_2 is already part of the conventional route or the CCU route is already commercialized. For example, the conventional urea production already uses CO_2. Here, additional improvement on sustainability aspects lies in upstream processes like ammonia synthesis, which are not part of this study. One prime example for CCU application is the CO_2-based polyols from Covestro.[115] This company is driving CO_2 utilization at their NRW sites forward, but since this study is focusing on new/additional CCU applications, this idea was not considered for the filtered list. Another reason for excluding options was the lack of sufficient available data about the process, which was especially the case for processes with very low TRL's.

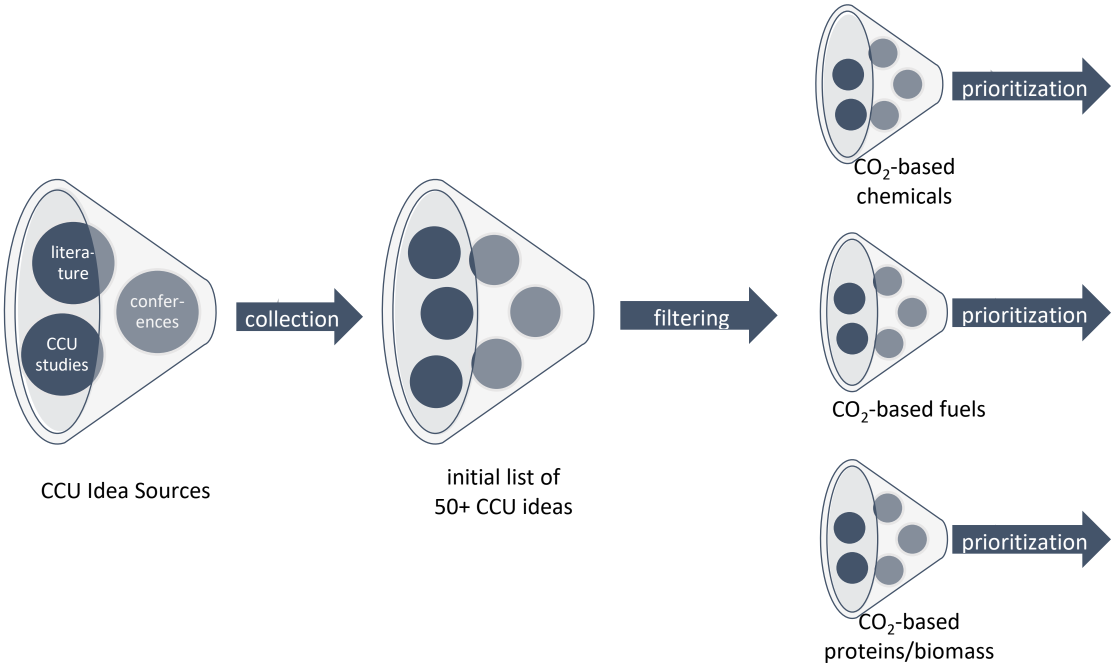

Figure 5-4: Schematic process of CCU idea collection and filtering process.

Additionally, the initial list contained several CCU options, that were based on either methanol or syngas. If syngas is produced by utilizing CO_2 it could have a significant impact to improve the carbon footprint of plenty processes. As a consequence, the filtered list contains three syngas production options, that were evaluated on a deeper level. However, syngas-based CCU pathways, where syngas is used as an input flow to create a specific product, were mostly filtered out and not reviewed. As representative example, kerosene production was selected for assessment. For these options it has to be kept in mind, that syngas can only be transported over short distances. It is not viable, that the pure syngas production would be

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[115] https://solutions.covestro.com/de/marken/cardyon, accessed 22.09.2021

outsourced in regions with location advantage like cheap solar energy in sunny regions, but the overall production chain to the final product.

On the other hand, green or CO_2-based methanol can play an important role in the future of sustainable chemical production. Methanol is already today one out of four essential base chemicals and about 66% are used for production of other chemicals.[116] Replacing conventional methanol by a green alternative would contribute significantly to the CO_2 footprint reduction of the chemical industry. Industry experts expect that methanol will be implemented as a platform chemical and it might be the energy carrier of the future, which would lead to a much bigger methanol demand

If additional methanol supply is required it is worthwhile to implement sustainable pathways not considered so far. Because of that, CCU pathways, providing the target product methanol were judged as solid fit for the CCU study. Four pathways were reviewed for methanol production involving CO_2 utilization. Methanol exhibits one significant advantage: as a liquid, it is easy to handle. Storing, transportation and distribution is much more practically feasible than for gas or electricity. As mentioned above, methanol is a platform chemical and can be converted into numerous other chemicals. The study's initial list contained several of methanol-based options, which are not commercially applied yet. Even though these options might be more relevant in a future CO_2-based industry, it would not be reasonable to review all options in detail within this study. Three pathways were chosen exemplarily for the filtered list and evaluated on a deeper level. As a conclusion, methanol and syngas do have a convincing fit to be produced by utilizing CO_2 in the production process. Hence several options for methanol or syngas production were chosen for the assessment, while most options using methanol or syngas as a feedstock were filtered out.

This first reviewing process transformed the initial list into the filtered list (Table 5-6). It contains roughly 40 options, that were divided into three categories: chemicals (34), fuels (7) and proteins (6) to be evaluated on a detailed level. The assessment of the CCU options was conducted by the following steps:

1. Criteria Catalogue (see chapter 5.1)
2. Research for reliable data: A matrix with needed data was filled out (e.g. energy requirement, mass flows, CO_2 demand and etc.)
3. Evaluation of the scores: The data (step 2) were evaluated by the principles of the criteria catalogue (step 1)

This assessment led to a prioritization of the CCU options in the three areas, which will be discussed in chapter 5.6, being the basis for the concept phase (Part C of this study).

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[116] IRENA and Methanol Institute, 2021, Innovation Outlook: Renewable Methanol

Table 5-6: Filtered lists with CO$_2$-based chemicals, fuels and protein/biomass options.

	Product	Process
Chemicals	Acetic Acid	- from methanol and CO - CH_4 plus CO_2 - bio-electrical CO_2 conversion
	Acrylic Acid	- from ethylene and CO_2 - from CO_2-based methanol via propylene - from 3-hydroxy-propionic-acid
	C4 to C6+ Aldehydes[117]	oxo-process for - butyraldehyde - valeraldehyde
	C4 to C6+ Acids[117]	oxo-process for - hexanoic acid - ethyl-hexanoic acid
	Ethanol	- from DME (via CO_2-based methanol) - via gas-fermentation
	Propanol	- from ethene
	n-Butanol	- from ethanol - via gas-fermentation
	Hexanol	via gas-fermentation
	Carbon Black	- CH_4 splitting - CO_2 splitting - reverse-water-gas-shift reaction
	DMC	- from ethylene carbonate - from fossil methanol and CO_2
	Ethylene	electrocatalytic production
	Formic Acid	- electrochemical - hydrogenation - photoelectrochemical
	Methanol	- bio-based - catalytic - electrochemical - photoelectrochemical
	Propylene Carbonate	catalytic from propylene oxide and CO_2
	Sodium bi-Carbonate	carbonation of sodium carbonate
	Sodium Carbonate	from NaOH waste streams and CO_2
Fuels	Kerosene	Fischer Tropsch process
	Syngas	- co-electrolysis - thermochemical - dry methane reforming
	Methanol to Gasoline	with DME as intermediate product
	DME	- catalytic process, $CO_2 + H_2$ - bi-functional catalyst for CO_2 to Methanol and dehydration to DME in one step
	SNG	catalytic hydrogenation
Protein rich biomass	Tomatoes	conventional greenhouse cultivation - general baseline for matrix
	Microbial Proteins	gas fermentation
	Lemna	indoor cultivation
	Microalgae (protein rich biomass only)	indoor cultivation
	Microalgae + high valuable (E18)	indoor cultivation
	Nutraceutical (astaxanthin)	indoor cultivation - as reference for single high valuable production

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[117] Note: typically a mix of alcohols and aldehydes are produced within the common oxo-process, representative chemicals for low value / high volume and high value / low volume examples have been chosen to reflect the bandwidth of possible chemicals.

5.6 Prioritization of CCU Ideas

The selected CCU ideas from chapter 5.5 in the three areas – fuels, chemicals and proteins – were prioritized as described in chapter 5.1. A sensitivity analysis based on the theoretical energy demand and a more realistic energy demand as outlined in 5.1 of the CCU options showed, that the overall scoring did not change significantly, with the exception of ethylene, which dropped from position 7 down to 30.

The discussion of the results will be done separately in the following subchapters.

5.6.1 CO_2-based Chemicals

The scoring of the selected CO_2-based chemicals within the five categories and the final score under realistic assumptions is summarized in Table 5-7. The intended impact of the environmental compatibility and economic feasibility can easily be noticed.

Table 5-7: Priority of CO_2-based chemical options. The average scores and ranking are based on the more realistic assumptions, the ranking based on the theoretical assumptions is given for comparison.

CO_2-based chemicals	**Technical**	**Infrastructure**	**Environmental compatibility**	**Economic feasibility**	**Rollout scenario**	**Score**	**Priority (theor.)**	**Priority (real)**
Valeraldehyde	0.40	0.15	1.43	0.60	0.17	2.76	1	1
Formic Acid - hydrogenation	0.00	0.07	1.76	0.48	0.34	2.66	3	2
Formic Acid - electrochemical	0.37	0.08	1.24	0.48	0.29	2.48	2	3
Acrylic Acid - from methanol via propylene	0.53	0.08	1.15	0.53	0.17	2.47	6	4
Acrylic Acid - from Ethylene and CO_2	0.11	0.14	1.28	0.58	0.27	2.38	7	5
Acetic Acid - direct synthesis	0.00	0.14	1.43	0.54	0.26	2.36	19	6
Formic Acid - photoelectrochemical	0.24	0.09	1.24	0.48	0.19	2.25	4	7
Polypropylene Carbonate	0.40	0.09	0.93	0.66	0.14	2.21	21	8
DMC - from Ethylene Carbonate	0.27	0.08	1.01	0.67	0.09	2.12	24	9
Sodium bi-Carbonate	0.53	0.15	0.69	0.52	0.23	2.12	18	10
DMC - from fossil Methanol and CO_2	0.00	0.07	1.28	0.67	0.09	2.11	17	11
Acetic Acid - fossil Methanol & green CO	0.51	0.14	0.59	0.54	0.26	2.03	12	12
Acrylic Acid - from 3-HPA	0.11	0.09	1.18	0.32	0.27	1.97	8	13
Acetic Acid - green Methanol & green CO	0.51	0.11	0.65	0.32	0.26	1.85	16	14
Carbon Black (RWGS and Boudouard)	0.00	0.08	1.18	0.09	0.36	1.71	5	15
Methanol - bio-based	0.40	0.11	0.62	0.16	0.34	1.63	14	16
Acetic Acid - bio-electrical	0.13	0.11	0.89	0.23	0.26	1.63	20	17
Methanol - catalytic	0.53	0.08	0.36	0.28	0.34	1.59	13	18
C4 Butanol - gas fermentation	0.27	0.08	0.86	0.13	0.24	1.57	11	19
Butanal/Butyraldehyde	0.40	0.12	0.33	0.39	0.32	1.56	23	20
Methanol - electrochemical	0.11	0.12	0.62	0.24	0.42	1.51	27	21
Methanol - photoelectrochemical	0.11	0.12	0.62	0.24	0.42	1.51	28	22
C4 Butanol - from Ethanol	0.13	0.07	0.86	0.13	0.24	1.43	15	23
Sodium Carbonate	0.00	0.15	0.54	0.43	0.31	1.43	32	24
C4-C6+ Acids (here: Ethyl-hexanoic acid)	0.40	0.12	0.00	0.52	0.28	1.32	25	25
Acetic Acid - green Methanol & gray CO	0.53	0.12	0.06	0.32	0.26	1.29	30	26
C2 Ethanol - gas fermentation	0.53	0.02	0.12	0.04	0.57	1.29	10	27
C2 Ethanol - from DME	0.40	0.04	0.12	0.00	0.59	1.15	26	28
C6 Hexanol - gas fermentation	0.27	0.09	0.00	0.35	0.40	1.12	29	29
Ethylene (C_2H_4)	0.11	0.06	0.12	0.07	0.59	0.95	9	30
C4-C6 acids (example Hexanoic Acid)	0.24	0.11	0.00	0.26	0.21	0.82	31	31
C3 Propanol - from Ethene	0.13	0.09	0.30	0.19	0.11	0.82	34	32
Carbon Black (CH_4 splitting)	0.13	0.08	0.00	0.04	0.36	0.62	33	33
Carbon Black (CO_2 splitting)	0.00	0.08	0.12	0.00	0.21	0.40	22	34

In view of the variety of assessed chemicals, additional filters were applied to further narrow down the list of thirty-four CCU pathways, instead of using the priority list as is. The aim of this study is to identify promising results especially for NRW, which should contribute to climate change efforts, but also in securing employment in this area. One applied filter was therefore, to consider only CCU options, which have a CO_2 reduction potential for NRW larger than 30 kt/a. Additionally, economic viability is crucial for the realization of CCU ideas on commercial scale. As long as no regulation is put in action to support CO_2-based chemical options, competition against the conventional (fossil-based) chemical will be the reality. A positive economic viability according to the definition in section 5.1 does not mean, that there is a positive business case of respective process. It is rather a first assessment if the costs for required raw materials and energy demand would be covered by the market price. Table 5-8 provides on overview of CCU options, where at least one of the pathways has a positive economic viability. CCU pathways with significant demand for hydrogen fail to achieve positive economic feasibility due to the high costs assumed for green hydrogen production. Basically, this applies to CO_2-based alcohol production which require relatively more hydrogen compared to CO_2-based acid production. Thus, CO_2-based chemicals where all CCU pathways show a negative economic viability, are summarized separately in Table 5-9.

*Table 5-8: Filtered priority list for CCU chemicals with CO_2 reduction potential in NRW higher than 30 kt/a and at least one pathway with positive economic viability. *marks pathways with negative economic viability.*

CO_2-based chemicals	Priority (real)	Priority (theoretic)	TRL	Infrastructure	Environmental	Economics feasibility	Rollout scenario	Carbon FP reduction potential NRW [ktCO_2/a]	Economic viability ε [-]	theoretical energy demand w/o H_2 [MWh/t]	H_2 demand [MWh H_2 / t product]	energy demand incl. H_2 for NRW roll-out scenario [GWh/a]
Formic Acid												
hydrogenation	2	3	3	0.07	1.76	0.48	0.34	154	0.9	3.1	2.4	482
electrochemical	3	2	6	0.08	1.24	0.48	0.29	165	0.4	4.4		393
photo-electrochemical	7	4	4	0.09	1.24	0.48	0.19	165	0.4	4.4		393
Acrylic Acid												
from MeOH-based propylene	4	6	9	0.08	1.15	0.53	0.17	258	9.4	0.4	13.7	2,009
from ethylene (fossil) and CO2	5	7	3	0.14	1.28	0.58	0.27	242	2.8	0.4		55
combination bio-tech & conventional*	13	8	1	0.09	1.18	0.32	0.27	412	3.0	1.7	18.9	2,946
Acetic Acid												
direct synthesis (NG + CO2)	6	19	1	0.14	1.43	0.54	0.26	338	1.6	0.3		66
conventional: gray MeOH & green CO	12	12	8	0.14	0.59	0.54	0.26	205	0.7	2.5		529
conventional: green MeOH & green CO*	14	16	8	0.11	0.65	0.32	0.26	287	-0.2	2.7		562
bio-electric*	17	20	4	0.11	0.89	0.23	0.26	351	-0.4	8.1		1,711
conventional: green MeOH & gray CO*	26	30	9	0.12	0.06	0.32	0.26	83	-0.4	0.6		128
DMC												
from MeOH and CO2	11	17	3	0.07	1.28	0.67	0.09	36	2.5	1.0		24
from ethylene carbonate	9	24	6	0.08	1.01	0.67	0.09	16	0.8	0.1		3
Oxo-Chemicals												
Valeraldehyde	1	1	8	0.15	1.43	0.60	0.17	70	2.8	3.6	1.2	62
Butyraldehyde*	20	23	8	0.12	0.33	0.39	0.32	30	0.0	4.9	1.5	472

*Table 5-9: Filtered priority list for CCU chemicals with CO_2 reduction potential in NRW higher than 30 kt/a, but without any pathway with positive economic viability. *marks pathways with negative economic viability.*

CO_2-based chemicals	Priority (real)	Priority (theoretic)	TRL	Infrastructure	Environmental	Economics feasibility	Rollout scenario	Carbon FP reduction potential NRW [ktCO_2/a]	Economic viability ε [-]	theoretical energy demand w/o H_2 [MWh/t]	H_2 demand [MWh H_2 / t product]	energy demand incl. H_2 for NRW roll-out scenario [GWh/a]
Methanol (benchmark)												
Bio-based*	16	14	7	0.11	0.62	0.16	0.34	419	-0.7	4.0		1,160
Catalytic*	18	13	9	0.08	0.36	0.28	0.34	145	1.8	0.3	10.3	3,063
Electrochemical*	21	27	3	0.12	0.62	0.24	0.42	282	-0.5	7.0		2,038
Photoelectrochemical*	22	28	3	0.12	0.62	0.24	0.42	229	-0.6	8.9		2,583
Ethanol (benchmark)												
from MeOH-based DME*	28	26	8	0.04	0.12	0.00	0.59	113	1.0	0.8	15.2	5,580
gas-fermentation (CO2 + H2)*	27	10	9	0.02	0.12	0.04	0.57	0	-0.5	7.2	14.0	7,417
n-Butanol (benchmark)												
gas fermentation (CO2 + H2)*	19	11	6	0.08	0.86	0.13	0.24	21	0.7	4.5	17.7	297
EtOH-based*	23	15	4	0.07	0.86	0.13	0.24	20	0.6	4.9	17.7	303
Ethylene*	30	9	3	0.06	0.12	0.07	0.59	257	-0.8	38.6		26,890

The resulting prioritization list for chemicals shows 16 CCU options for eight different chemicals, as some chemicals could be realized with different CO_2-based pathways. Some of them, would combine fossil resources (like ethylene and natural gas) and CO_2. Top candidates appear to be formic acid, acrylic acid and acetic acid.

Some CCU options – such as ethanol and butanol/hexanol – were included in this assessment as a benchmark process, as similar technologies are currently under development by industry consortia (e.g. Steelanol project by LanzaTech and ArcelarMittal for ethanol and Rheticus by Evonik/Siemens for butanol/hexanol). One major difference to the Steelanol project is the feedstock as the real project actually considered steel off-gases (mixture of $CO/CO_2/H_2$) and requires less energetic input than the CO_2/H_2-based approach considered within this study.

This study intends to elaborate CO_2-based options, which are currently not under development, but bear promising potential for CO_2 reduction efforts. At this point, further development should consider involvement of relevant stakeholders, covering the overall value chain, realistic sites, industrial and market demands.

5.6.2 CO_2-based Fuels

Table 5-10: Prioritized results of CO_2-based fuel assessment.

CO_2-based fuels	Technical	Infrastructure	Environmental compatibility	Economic feasibility	Rollout scenario	Score	Priority (theoretic)	Priority (real)
FT-kerosene	0.53	0.07	1.15	0.21	0.42	2.38	1	1
Syngas - co-electrolysis	0.37	0.15	1.09	0.47	0.13	2.21	2	2
Methanol to fuel	0.53	0.13	0.39	0.30	0.50	1.85	3	3
Syngas - thermochemical	0.27	0.11	0.83	0.38	0.13	1.71	4	4
DME	0.13	0.09	0.53	0.54	0.17	1.47	6	5
SNG - catalytic hydrogenation	0.40	0.07	0.12	0.52	0.50	1.60	5	6
Syngas - DMR	0.27	0.13	0.00	0.03	0.13	0.55	7	7

In case of CO_2-based fuels, regulation based on the RED II will alter the economics significantly. Therefore, pathways with a negative economic viability based on the methods used in this study, will not be excluded from discussion.

Fischer-Tropsch-based kerosene appears to be the most promising option, which is mainly due to the market size and high (future) CO_2 footprint reduction potential. Additionally, it should be noted, that synthetic kerosene is commonly seen as the most promising option to decarbonize the aviation sector. Runner-up is syngas (2:1) based on co-electrolysis. The main difference between these two options is, that kerosene can be transported long distances, while syngas is typically produced on-site where it is further converted. The following options with a similar final score are methanol to fuel, for which gasoline was considered since the conversion to kerosene is in early development phases, and the thermochemical production of syngas. SNG is close to those options, but due to very low emissions in the conventional process of extracting natural gas, the CCU option needs energy with a low carbon footprint and thus the environmental score is very low. The DME option has a low score in the rollout category due to a comparatively small market in the EU. At the last position, syngas via dry methane reforming is found due to low scores in the environmental and economic category. The first is caused by the usage of methane, while the second is caused by the need of CO_2 and H_2 (to achieve a 2:1 mixture).

This outcome is not unexpected as there are several ongoing PtL projects, targeting kerosene or methanol. A recent review from Wulff et al.[118] assessed 220 PtX projects, with one third of those processing hydrogen into fuels and products. Methanation appears to be the major focus, with some projects aiming at methanol and kerosene.

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[118] Wulf et al., 2020, Review of Power-to-X, Demonstration Projects in Europe, Front. Energy Res.

5.6.3 CO_2-based Protein / Biomass Production

The third category within this study is biomass / proteins and considers different product areas from general produce to protein rich biomass to single cell proteins and nutraceuticals. Overall, five different options were evaluated, which are presented briefly in the following. For each option, one process was selected and considered as representative for the respective product, well knowing that different suppliers are available for most of the discussed pathways. The aim was to have a high-level comparison of the different product types and to identify their potential within the NRW region.

All options have in common that they need CO_2 to grow the respective biomass, which is a natural carbon sink. The amount of CO_2 needed ranges from 0.6 kg to 2.0 kg per kilogram biomass. Additional input streams are water, nutrients, heat and light, which can vary depending on the selected process. Using artificial light instead of natural sunlight increases demand for electricity significantly and the impact will be seen during the assessment.

Tomatoes (Greenhouse Production)

Addition of carbon dioxide to greenhouse air can increase the yield of tomato production. Growth enhancement with CO_2 is common in greenhouse cultivation and is already considered state-of-the-art for example in the Netherlands. Tomatoes were selected as representative for greenhouse produce as sufficient data is publicly available. Looking at Germany and NRW itself, horticulture is an important industry sector. Vegetables are cultivated on over 20,000 ha (indoor 227 ha), which is combined with an employment of over 8,000 jobs.[119]

Lemna (Vertical Farming Indoor)

Lemna (also known as duckweed) is a species of aquatic freshwater plant. The nutritional value of Lemna is very high, showing high protein content, balanced amino acid and fatty acid profile and containing essential vitamins and minerals. Subsequently duckweed can be used as livestock feed component and potentially as alternative plant-based protein for human consumption. In North Rhine-Westphalia, the companies Oxygenisis and LemTriCon are developing a vertical farming style greenhouse production process for Lemna, which forms the basis for the assessment undertaken in this study.

Microbial Proteins (via Gas Fermentation)

This fermentation process uses a microorganism and input streams, like hydrogen, carbon dioxide and nutrients to grow single cell proteins. Microbial protein is a potential alternative protein source for human consumption. The process is currently being demonstrated by the Finnish company Solar Foods, using the trademark “Solein” which is working towards the approval as novel food within the EU. The assessment within this study is based on information provided by Solar Foods directly during an expert interview and by referring to respective literature from Sillman.[120,121]

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[119] https://www.gartenbaunrw.de/index.php/gartenbau/obst-und-gemuesebau, accessed 23.09.2021

[120] Sillman et al, 2019, Bacterial protein for food and feed generated via renewable energy and direct air capture of CO2: Can it reduce land and water use?, Global Food Security

[121] Sillman et al, 2020, A life cycle environmental sustainability analysis of microbial protein production via power-to-food approaches, The International Journal of Life Cycle Assessment

Microalgae

Depending on the selected microalgae strain, the properties of the resulting biomass can differ in respect to protein, fatty acid and nutraceuticals content. Different cultivation systems have been developed: open ponds, tubular systems, flat panels, hanging bags and more. The selection of the cultivation system depends on several factors like climate zone and sunlight hours. An installation in North Rhine-Westphalia should consider a closed (indoor) system with potentially additional lightning and heat input. During the study expert interviews with representatives from Omega Green (located in the Netherlands) were conducted. They were primarily chosen because of their experiences with multiple large-scale microalgae pilot and demo plants.[122] Additional information was provided for the detailed assessment by Omega Green. Two different options were considered: one just focusing on the overall biomass produced, which could be used as animal feed. The second case considers the extraction of a high value compound like the food colorant E18 first and using the remainder of the biomass for the feed sector.

Nutraceuticals (Astaxanthin)

Astaxanthin, a carotenoid, is a high-value nutraceutical which can be produced by microalgae in a designated indoor cultivation set-up. The company Subitec[123] has designed and installed a 1 ha indoor facility in the Czech Republic (Algamo Ltd.)[124] which forms the basis for the assessment within this study. This option is representing a high-value – low volume product case, while the other protein/biomass cases have in general a larger market volume.

Evaluation Matrix

The evaluation of these options was based on the same criteria catalogue as described in chapter 6.1. But some criteria have been adapted for the biomass group or were excluded. The comparison to conventional protein / biomass production is a very complex topic as above options are not necessarily a one-on-one replacement of one specific product – in opposite to the drop-in chemicals discussed in chapter 5.6.1. Therefore, the environmental compatibility assessment was mainly based on the stoichiometric CO_2 demand for production and the carbon footprint of the respective technology itself (current and future). The scoring for toxicity was omitted as it was considered similar for all assessed options. Additionally, a comparison of more sustainability driven factors like land and water use, energy demand between the CCU options and typical protein sources is done separately to the scoring. Due to confidentiality of some data, only the final scoring will be published within this study.

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[122] https://www.omegagreen.nl/innovation/, accessed 23.09.2021

[123] Presentation by H. Hyttinen from Subitec on CeBiTec conference in Bielefeld, 25.09.2017

[124] https://www.algamo.cz/index.php/en/homepageen/, accessed 23.09.2021

Table 5-11: Prioritized results of CO_2-based protein / biomass assessment.

CO_2 -based proteins / biomass	Technical	Infrastructure	Environmental compatibility	Economic feasibility	Rollout scenario	Score	Priority
Tomatoes	0.64	0.05	1.49	0.47	0.24	2.90	1
Lemna	0.51	0.05	1.26	0.42	0.39	2.62	2
Microbial proteins	0.45	0.02	1.10	0.58	0.19	2.34	3
Microalgae: biomass/(E18)	0.51	0.05	0.39	0.61	0.43	1.99	4
Microalgae: biomass only	0.37	0.05	0.39	0.32	0.42	1.55	5
Nutraceutical: Astaxanthin	0.64	0.05	0.00	0.58	0.22	1.48	6

The overall scores summarized in Table 5-11 are in a rather narrow field between 1.5 to 2.9 (from theoretical 0 to 4). The outcome of tomatoes as the best option is connected to the fact, that it has the lowest carbon footprint (current and future scenario) of the assessed biomass options. Since environmental compatibility was ranked with the highest priority (46%) compared to other criteria, it had the biggest impact. The same applies to the chosen nutraceutical, which by design has a high energy demand, causing a poor carbon footprint compared to the other options. One needs to have in mind, that these two cases (tomato and nutraceuticals) are the only two examples, which do not target protein production. They were included as general benchmarks for a bulk (tomato) and niche (astaxanthin) market. With respect to protein rich biomass production, the options score between 1.55 to 2.62. Strong differences can be seen on the environmental compatibility, which are mainly caused by the assumed energy / heat demand for the different processes. As all these options are still under development, further improvement might be achievable over time.

At this point, the discussion within this section can be shifted from the pure CCU focus to a more sustainability focused discussion about the future protein supply within NRW.

The UN frequently highlights the challenge, that the worldwide population will grow to 9.6 billion people in 2050. To feed the world in 2050 the food production must grow by 70%.[125] This problem gets harder to solve, having in mind, that climate change will lead to less arable land and water available. Further, the claim for sustainable agriculture with less use of pesticides and genetically-modified seeds is growing.

NRW is an important player in the animal feed production segment as well a key region for pork farming. With 4 Mio t/a of feed production, NRW is the second biggest producer in Germany.[126] Therefore, growing protein-rich biomass in the Rheinisches Revier as livestock feed could be a good match.

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[125] https://news.un.org/en/story/2013/12/456912, accessed 23.09.2021

[126] https://www.landwirtschaftskammer.de/wir/pdf/agriculture-in-nrw.pdf, accessed 23.09.2021

Table 5-12: Overview of protein types and impact on CO_2 footprint, land and water use, energy demand collected from literature and own assessments.

	Protein content [%]	CO_2 FP [kg CO_2 / kg protein]	Land Use [m^2/kg protein]	Water Use [kg/kg protein]	Energy [MJ/kg protein]
Beef	21[127]	75 - 170[128]	144 - 258[128]	15,415[128]	177 - 273[128]
Pork	21[127]	21 - 53[128]	47 - 64[128]	5,988[128]	95 - 236[128]
Chicken	22[127]	18 - 36[128]	42 - 45[128]	4,325[128]	80 - 152[128]
Soybean	34[129]	0.9 - 3.7[128]	5.2 - 6.0[128]	6.3[128]	n.d.
Microbial protein – Literature[121]	58	0.8 - 1.2	0.03 - 0.06	1.0 - 3.8	79
Microbial protein – this study[130]	65	2.1	0.26	10	180
Microalgae[130]	50	32.6	0.57	71.4	617
Lemna[130]	40	3.1	0.08	13	263

In 2017, the Joint Research Center (JRC) of the EU commission, published a paper on the assessment of livestock farming and environmental impacts.[128] The CO_2 footprint commonly considers the GHG emissions occurring during the farming.[128] The use of water could further be divided into the type of water used for animal mast, but it also depends on how efficient the animals convert the feed, which might differ regionally. The JRC report is referring to the average amount of water needed. Table 5-12 shows the difference between conventional and sustainable/alternative protein production. In the literature, different approaches can be found to assess the sustainability of food sources. For this study one kilogram of protein as base unit were chosen and values from the literature were adapted accordingly.

In general, the conventional routes are much more demanding in terms of CO_2 footprint, land use and water use. In these three categories, soybeans are significantly more sustainable than conventional meat. Nevertheless, soybeans are mainly imported and there is a variety of discussion regarding the GMO-topic (genetic modified organisms) and the deforestation of the rain forest. The protein options described within this study are comparable with soybeans with regards to the CO_2 footprint, require less land but more water. Microalgae appear less sustainable than microbial protein and Lemna. This is partially due to the fact, that the assessed cultivation method is considering the use of available access heat from industrial sources and therefore, further optimization was not considered in this set-up. However, the

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[127] https://www.nu3.de/blogs/nutrition/eiweisshaltige-lebensmittel, accessed 23.09.2021

[128] JRC Tech Report, Fiore, G.; 2017, Farming and Food Security: An Assessment of Animal Productions and Environmental Impact

[129] Deutsche Forschungsanstalt für Lebensmittelchemie, Garching (Hrsg.): Lebensmitteltabelle für die Praxis. Der kleine Souci · Fachmann · Kraut. 4. Auflage. Wissenschaftliche Verlagsgesellschaft, Stuttgart 2009, ISBN 978-3-8047-2541-6, S. 239.

[130] Own calculations based on expert interviews

amount of heat was included in the life-cycle assessment, resulting in the high energy demand, which impacts the CO_2 footprint.

However, one needs to bear in mind that the assessments made within this study are based on different assumptions for example for energy supply than used in literature. Therefore, differences in the LCA results are to be expected. This can be seen well for the microbial proteins, where Table 5-12 is citing values from the literature and results from own assessments. Even though there are differences in the values, the overall trend remains the same and the protein rich biomass discussed within this study have the potential to become a sustainable alternative for the local food and feed market.

Conclusion and Outlook for Protein-rich Biomass

Among the presented options there is no clear winner, which should be chosen as the best way to realize a CCU biomass/protein option in NRW. Nonetheless, the evaluation reveals clear structures and trends, to identify the strength of the individual options from an objective standpoint. This is a helpful basis for decision making. In addition, it is necessary to consider arguments like local production of biomass, sustainability factors like water and land use and the possibility to use waste heat to satisfy the rather high heat demand for greenhouse operations. The trade-off for less land use and water consumption is the high energy demand. With increasing availability of renewable energy, the right balance could be achieved to feed the growing population.

The aim of this study with regard to the biomass/protein topic is to create a broader awareness of the solution space and to initiate discussions or even projects building up on these topics.

5.7 Limitations within NRW

In Part A of this study, the existing industry of NRW and its infrastructure was described. Currently, the feedstock of the carbon-based chemical industry is mainly imported in the form of crude oil or natural gas, while the energy supply is a mix of local energy production and imports from regions around NRW. Replacing parts of the fossil carbon feedstock by CO_2-based alternatives requires significant amounts of renewable energy, either in the form of renewable electricity or in the form of green (renewable) hydrogen supply. The top 15 CO_2-based chemicals assessed in part B of this study (chapter 5) – representing only a small fraction of the local chemical industry – have a combined CO_2 reduction potential of approximately 1.2 Mt/a based on NRW demand (based on future energy mix described in section 5.1). The energy demand for these 15 selected chemicals is about 1.9 TWh/a and additionally 10.8 TWh/a of hydrogen supply are required. In case of CO_2-based fuels, these values will be much higher as fuels are produced in a much larger volume than chemicals.

Table 5-13: Overview energy demand for production of selected chemicals and kerosene. Differentiating between electrical energy and energy demand for hydrogen production. Product capacities reflect NRW demand.

	NRW demand [Mt/a]	CO_2 FP reduction [Mt CO_2/a]	relative energy [MWh/t CO_2 reduced]	energy demand w/o H_2 [TWh/a]	H_2 demand [TWh/a]
15 top chemicals	1.4	1.2	10.2	1.9	10.8
kerosine	3.1	4.9	14.1	1.4	67.5

Table 5-13 provides a simplified view on the energy demand required to avoid one ton of CO_2 emissions for the selected CCU pathways. Within the chemical section this energy demand varies from 0.2 to 49.6 MWh/t$CO_{2\ \text{avoided}}$ due to the large variety of products, but a clear trend can be seen: the total energy demand, including hydrogen is significantly lower for chemicals (average of 10.2 MWh/t$CO_{2\ \text{avoided}}$) than for kerosene (14.1 MWh/t $CO_{2\ \text{avoided}}$)[131]. The main reason is the difference in oxygen content: while many chemicals contain some oxygen, kerosene does not contain oxygen and higher reduction energy is needed to remove all oxygen from the CO_2 feedstock. A differentiated look at the energy demand for electricity and heat versus the energy demand for renewable hydrogen production, shows a more complex picture. The average energy demand (for electricity and heat) is almost threefold for chemicals compared to kerosene while the energy demand for hydrogen is for chemicals only about 37% of kerosene hydrogen demand.

These numbers indicate, that the pure energy demand for production facilities of the selected CO_2-based chemicals can most likely not be integrated / covered by the existing transmission network and respective expansion would be required. Thus, the high demand for hydrogen represents a challenge in itself and shows how crucial an overall roadmap and realization of renewable (and affordable) hydrogen supply is for a successful transition to renewable chemical feedstock supply.

From a feedstock point of view, an additional approach is possible. The current feedstocks for carbon-based chemicals and fuels are mainly crude oil or natural gas – both are imported feedstocks. Part B of the study focuses on drop-in chemicals, based on CO_2 directly using a variety of technologies, like thermochemical, biotechnological or electrochemical processes. However, most carbon-based chemicals could be synthesized based on methanol. Discussions with industry representatives revealed, that methanol-based synthesis is feasible, but required investments for changing the current processes would only be considered, if sufficient green methanol would be supplied at acceptable costs.

The CO_2-based fuels require basically a quite similar feedstock: syngas (e.g. a dedicated mix of CO and H_2). Conventionally, this feedstock is processed on site and not transported over longer distances. Theoretically, syngas could be mixed on site by hydrogen supplied via a pipeline infrastructure and local CO production. However, CO_2 reduction to CO at sufficient scale for fuel production is not available so far and according to Haldor Topsoe, their eCO process for CO production is intended to be scaled up by 2029 to 2,000 Nm^3 (~ 22 kt/a)[132]. For smaller scale applications in the chemical sector, this might be a viable solution. Therefore, CO_2-based fuels production in NRW will require significant amount of electricity in order to produce the required syngas based on water and CO_2.

In order to avoid a high demand for renewable energy for feedstock production in NRW and considering the high cost of energy (due to surcharges on top of energy production), it would be reasonable to consider the feedstock production at more economic sites. These feedstocks, like methanol and fuels, could then be imported to transform the local industry to more sustainability. This option will be considered in the concepts, described in the following part C of this study.

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[131] There are two CO_2-based chemicals pathways above 100 MWh/t$CO_{2\ \text{avoided}}$, which were not considered here.

[132] Küngas, 2020, Review—Electrochemical CO_2 Reduction for CO Production: Comparison of Low- and High-Temperature Electrolysis Technologies, Journal of The Electrochemical Society

6 Part C: Concepts for a Site in NRW

The final part of this study concludes with an exemplary concept for CO_2-based chemical production in NRW, using the insights gained in part A and B. The aim of the discussed concepts is not to present a detailed engineered case but to describe options, which could be deepened further with relevant stakeholders along the overall value chain. In general, there are different possibilities for any specific site: one would be focusing on the local demand of a given chemical (case 1), while another one would be assessing the available CO_2 source for conversion into a selected chemical (case 2). The latter case needs to consider the overall demand of the respective chemical in NRW or Germany in order to stay within realistic market opportunities. Comparison of these two different cases will provide first insights into the economics and economy of scale discussion, which could be used later on to identify a reasonable production capacity. The selected site and selected CCU processes will be described in detail in the following sections. The advantage of the chosen processes is that they represent high and low TRL options and that the high TRL options allow for a modular concept, e.g., focusing only on the production of the chemical and optionally also at the local feedstock production (like hydrogen and CO_2-based methanol). This is in line with the discussion in chapter 5.5, describing CO_2-based (“green”) methanol as potential new import feedstock.

6.1 Description of Chemical Site

To further specify the boundary conditions at the production site, a suitable location was chosen. Considering the infrastructure evaluation and through discussions, chemical parks emerged as a highly attractive option for such plants. NRW contains 1/3 of the chemical parks in Germany, with three of them being in the Rheinisches Revier.[133] One of them is the chemical park in Knapsack, operated by YNCORIS GmbH & Co. KG, which was founded in 1907.[134] Over 30 companies operate in this park, among them BASF SE, Bayer AG, Clariant AG, CABB Group GmbH and Lyondellbasell Industries AG. It spans an area of 180 ha, with 80 ha in Knapsack and 100 ha in Hürth – well connected via road, train and pipelines. An extension of additionally 16 ha is planned in the near future (see Figure), for which a focus is put on circular economy and topics such as CCU, CCS and PtL.

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[133] https://chemicalparks.com/chemical-parks/list-of-chemical-parks, accessed 22.09.2021

[134] https://www.chemiepark-knapsack.de/standort/zahlen-und-fakten/?L=222, accessed 22.09.2021

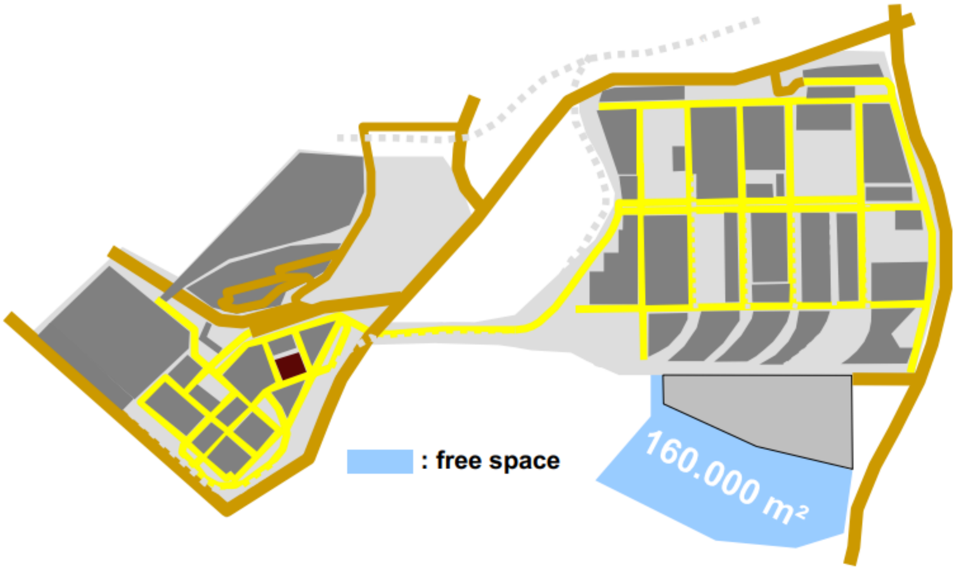

Figure 6-1: Planned extension of the chemical site Knapsack (provided by YNCORIS GmbH & Co. KG).

Some of the current products of the chemical park are polyvinyl chloride (PVC), polypropylene (PP), de-icing agents and monochloroacetic acid. Precursors of the last two products are respectively formic acid and acetic acid, which have obtained previously a high score in the rankings performed in part B of this study.

Due to the match of the required chemicals with the given criteria catalogue as well as the location in the Rheinisches Revier, the chemical park in Knapsack was chosen as the chemical site. The concept within this study considers that the production of acetic acid is based on methanol and carbon monoxide, as this reflects the current state-of-the-art technology. In order to have a CO_2-based acetic acid, the concept considers the production of CO_2-based methanol either optionally on-site or as imported feedstock.

6.2 Selected Processes

6.2.1 Carbon Capture Plant

One option as a CO_2 source for utilization could be the waste-to-energy plant from EEW Energy from Waste Saarbrücken GmbH located within the chemical park in Knapsack. It is a rather new plant (commissioned in 2009) and treats local commercial and industrial waste with high heating values.[135] Due to this set-up and its integration into the chemical park, it is very likely, that this waste-to-energy plant will be operated for many more years at a rather constant load. Hence, it would be a suitable CO_2 point source for carbon capture activities.

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[135] Standortflyer EBKW Knapsack, https://www.eew-energyfromwaste.com/fileadmin/content/Materialbestellung/EEW_Knapsack_2021-07_D_low.pdf, accessed 23.09.2021

The current state of carbon capture technology can be found in a recent report from the Global CCS Institute[136] and the International Energy Agency published a report on CCS on Waste to Energy[137]. According to the latter one, amine-based carbon capture technology is the most applied option for waste to energy plants and current installations in operation range from 4 kt/a to 100 kt/a CO_2 capture capacity. The largest CC plant on a waste to energy facility in operation is the AVR plant in Duiven, Netherlands, capturing up to 100 kt/a and supplying the captured CO_2 to local greenhouse horticulture.[138] The largest CC plant in planning is the Klemetsrud CC Plant from Fortum Oslo Värme, aiming at about 400 kt/a capture capacity.[139]

The cost of carbon capture strongly depends on the application, e.g., type of off-gas to be treated. CO_2 partial pressure has a strong impact on capture, but also the size of the required capture plant. According to the Global CCS Institute, the capacity of CC plants should be at least in the range of 400 to 450 kt/a.[136] Additionally, the cost of carbon capture is expected to be reduced by 50% by 2025, compared to 2010 and it is expected, that for low to medium partial pressure sources, like power plants, the capture cost could fall to 50 US$/t CO_2 in 2025.[136] This expectation is supported by the current trend observed from the recent large-scale installations cited by the Global CCS institute: the carbon capture costs at Boundary in Canada (commissioned in 2014) are reported to be 105 US$/t$CO_2$ and the Petra Nova retrofit plant in the US (commissioned in 2017) achieved capture cost of about 70 US$/t$CO_2$.

For the capture plant at the waste to energy plant in Knapsack, it was assumed that the capture costs will not be at the lowest expected costs cited by the global CCS institute, but in a similar range as for the Klemetsrud waste to energy facility in Oslo. Both plants are of comparable size and both are located in Western Europe, with similar cost assumptions for labor and construction work. However, the current project in Oslo considers CO_2 liquefaction and underground storage in the Northern Sea, increasing the total cost per ton of CO_2. In 2017, a feasibility study for the Oslo plant was conducted by Stuen[140] and the cost estimate distinguish the pure capture cost and energy demand for CO_2 liquefaction with an accuracy of +/- 40%. This suits the detail level of the concept envisioned in our present study. Based on this data, a capture cost of 89 EUR/t CO_2 was estimated for the waste to energy plant in Knapsack, the details are shown in the following table.

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[136] Global CCS Institute, March 2021, Technology Readiness and Costs of CCS

[137] IEAGHG Technical Report 2020-06, December 2020, CCS on Waste to Energy

[138] Press release AVR 30.09.2019: https://www.avr.nl/en/co2-installation/first-tons-of-co2-captured-from-residual-waste-supplied-to-greenhouse-horticulture/ , accessed 23.09.2021

[139] Fortum website: https://www.fortum.com/about-us/newsroom/press-kits/carbon-removal/fortum-oslo-varme-and-our-carbon-capture-project, accessed 23.09.2021

[140] Stuen, J., 2017, Feasibility Study of Capturing CO2 from the Klemetsrud CHP Waste-to-Energy Plant in Oslo. Energie aus Abfall

Table 6-1: Estimated capture cost for waste to energy plant in Knapsack based on Stuen[140] and IEAGHG report[137].

Carbon Capture plant	Amine-based, 90% carbon capture	
captured CO_2	288,000	t/a
CO_2 flow	36	t/h @ 8,000 h/a
energy demand	2.5	GJ/t CO_2
	200,000	MWh/a
CAPEX[140]	220	MEUR
OPEX[140]	11	MEUR/a
capture cost (accuracy +/- 40%[140])	89	EUR/t CO_2
expected range past 2025[136]	50–60	EUR/t CO_2
electricity demand (compression and liquefaction)[136]	2.8–3.2	MW

6.2.2 Acetic Acid

Initially, BASF SE developed the technology to produce acetic acid from methanol and carbon monoxide at high temperature and high pressure.[141] Further developments by Monsanto allowed low pressure operation and made it the preferred route for production. Celanese and BP respectively improved the Monsanto process by optimized catalyst selection and these two are currently the preferred technologies for acetic acid production from methanol and carbon monoxide. The carbonylation of methanol is described according to:

$$\mathrm{CH_3OH + CO \rightarrow CH_3COOH}\,,$$

$$\Delta H_\mathrm{R} = -138.6\,\frac{\mathrm{kJ}}{\mathrm{mol}}.$$

Initially, cobalt iodide catalysts were used for the exothermic process. Current developments, e.g., Celanese process and BP's Cativa process, use rhodium iodide and iridium-based catalysts. The route with rhodium is the option of choice for most plants globally. The selectivity with rhodium is above 99% for methanol and above 90% for carbon monoxide, respectively. Since polar solvents provide a rate enhancement, an acetic acid and water solvent medium is chosen. The amount of water could be reduced to below 14 wt.% through improvements from Celanese and adding Iridium salt even decreases the optimum to a water content of 2 wt.%. Primary byproducts are CO_2 and H_2 through the water-gas shift reaction:

$$\mathrm{CO + H_2O \rightarrow CO_2 + H_2}\,,$$

$$\Delta H_\mathrm{R} = -41.2\,\frac{\mathrm{kJ}}{\mathrm{mol}}.$$

Other byproducts in smaller amounts are CH_4, acetaldehyde and propionic acid. While the iridium-based synthesis route has primarily CO_2 and H_2 as byproducts, the amount of CH_4 byproduct is higher than for the rhodium-based route.

A liquid phase reactor operated at 150–200 °C and 30–60 bar is used for the carbonylation. Figure 6-2 shows the flowsheet of the process for the Monsanto process. The gaseous byproducts from the reactor

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[141] Le Berre et al., 2013, Acetic Acid, Ullmann's Encyclopedia of Industrial Chemistry

CO_2, H_2 and CH_4 are vented. The catalyst is recycled in the flash while the crude acetic acid is concentrated in three columns. The crude mixture contains among others propionic acid, methyl iodide, methyl acetate and water. Due to these separation units, the main energy demand of the plant is heat with about 0.389 kWh/kg of acetic acid while the electricity demand is about 0.057 kWh/kg.[142]

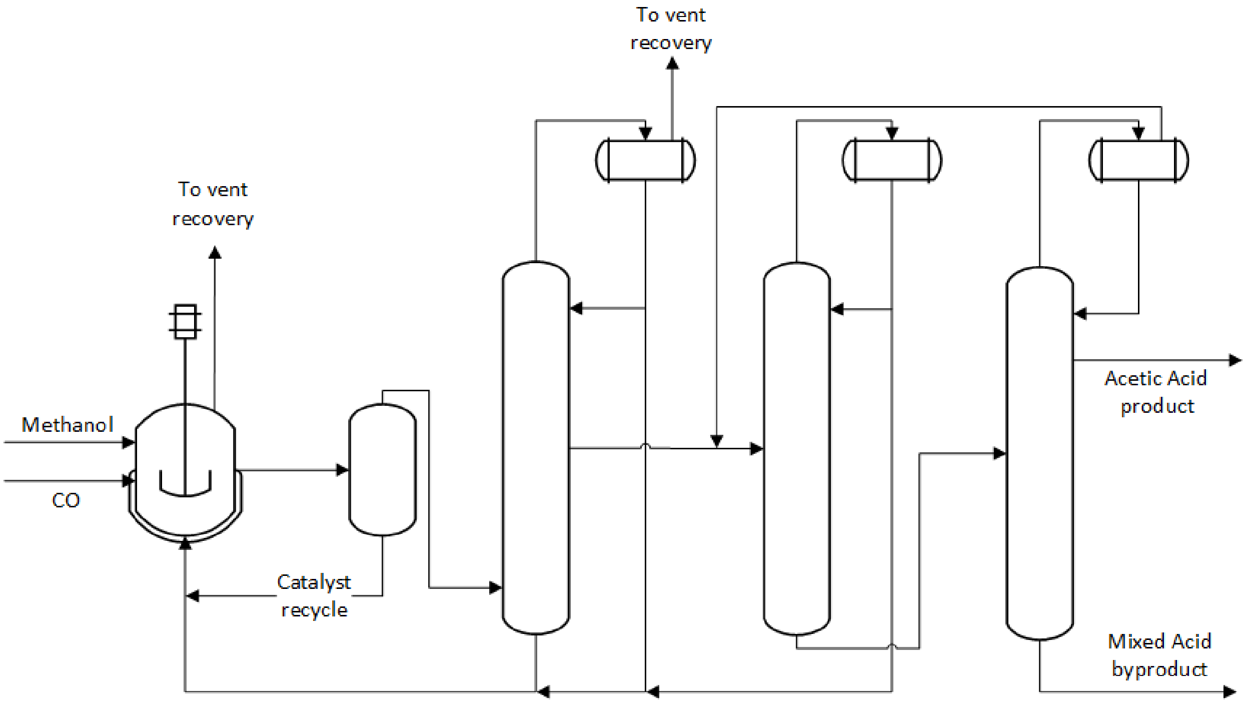

Figure 6-2: Flowsheet of the Monsanto process for acetic acid production (based on Le Berre et al. 2013[141]).

The Celanese and Cativa processes are well established commercially and provide already a good base for the usage in an economy based on CO_2 or green methanol. The cost for a plant with the conventional Cativa technology can be estimated to about 270 $MEUR_{2021}$ for a capacity of 300 kt/a.[143] The main cost driver for a renewable production would therefore be the cost of renewable CO or methanol.

6.2.3 Methanol

Methanol is commercially produced from syngas, with large-scale plants using the Lurgi MegaMethanol process. Feedstocks for conventional syngas for methanol production are mainly natural gas or coal, depending on availability and cost structure, while most production worldwide utilizes natural gas.[144] Acetic acid production can often be found in close proximity to methanol production sites to reduce transportation. The main reactions for methanol synthesis are:

$$\mathrm{CO} + 2\,\mathrm{H_2} \rightarrow \mathrm{CH_3OH}\,,$$

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[142] ecoinvent database 3.7; based on Althaus H.-J., 2007, Life Cycle Inventories of chemicals, ecoinvent report No. 8, v2.0. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH

[143] ICIS, https://www.icis.com/explore/resources/news/2002/10/16/182780/bp-formosa-jv-acetic-acid-plant-to-cost-around-200m/, accessed 22.09.2021

[144] Ott et al., 2012, Methanol, Ullmann's Encyclopedia of Industrial Chemistry

$$\Delta H_{\mathrm{R}\,(T=300\ \mathrm{K})} = -90.8\,\frac{\mathrm{kJ}}{\mathrm{mol}}\,.$$

and

$$\mathrm{CO_2} + 3\ \mathrm{H_2} \rightarrow \mathrm{CH_3OH} + \mathrm{H_2O}\,,$$
$$\Delta H_{\mathrm{R}\,(T=300\ \mathrm{K})} = -49.6\,\frac{\mathrm{kJ}}{\mathrm{mol}}\,.$$

As a side reaction, reverse water-gas shift takes place:

$$\mathrm{CO_2} + \mathrm{H_2} \leftrightarrow \mathrm{CO} + \mathrm{H_2O}\,,$$
$$\Delta H_{\mathrm{R}\,(T=300\ \mathrm{K})} = 41.2\,\frac{\mathrm{kJ}}{\mathrm{mol}}\,.$$

The total reaction is thus favored by high pressures and low temperatures. Initially, high pressure processes at 250–350 bar and 320–450 °C were common. These were then improved to the now state-of-the art low-pressure processes at 50–100 bar and 200–300 °C. A copper-based catalyst is industrially employed, which has a selectivity for methanol of above 99%. The reactor can generally be operated in an adiabatic or quasi-isothermal state. For the first, quenching of the reaction is achieved through adding cold gas along the length of the reactor. For the second approach, cooling is achieved by boiling water. A flowsheet of the MegaMethanol process, using a water-cooled and gas-cooled reactor, is shown in Figure 6-3.

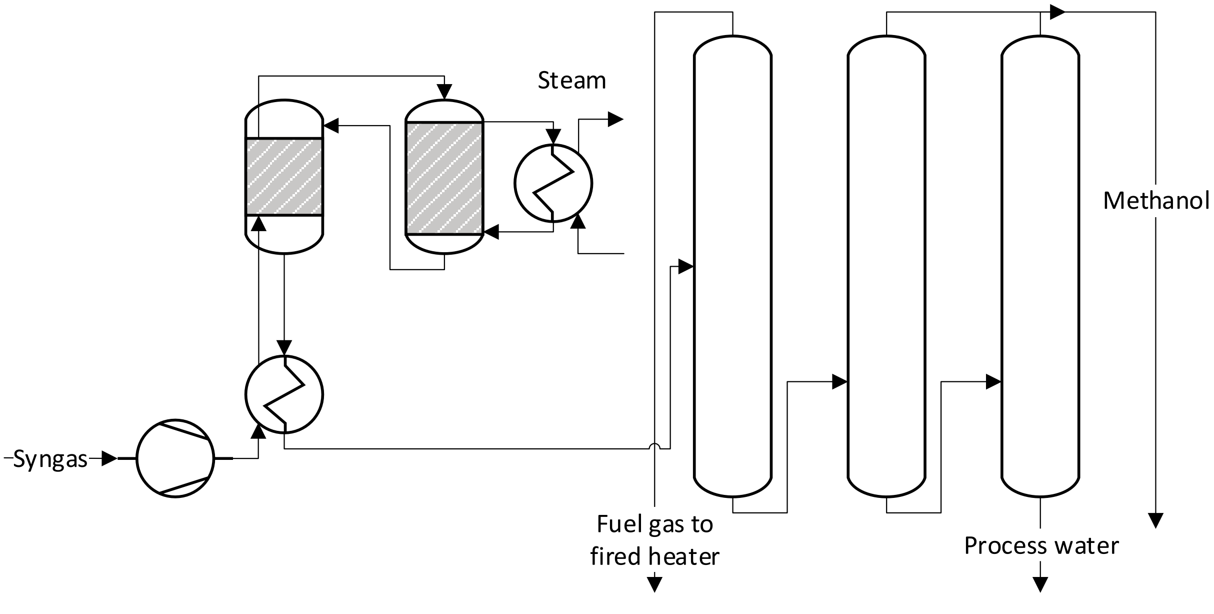

Figure 6-3: Simplified flowsheet of the methanol synthesis with the MegaMethanol process (based on Ott et al. 2013[144]).

The syngas is compressed and pre-heated first by the products and second by acting as a coolant for the second reactor. Afterwards it enters the reactor where catalysts are in the tubes and continues to the shell side of the second reactor with catalysts at the shell side. The temperatures are continuously

decreasing along the route, driving the conversion. After cooling and separation of unreacted gasses, the methanol is separated from the process water. Such plants can achieve capacities of up to 10,000 t/d.[145]
An alternative pathway which allows the direct use of CO_2 as a feedstock is the production through hydrogenation. The conditions for this reaction are similar to the syngas-based route, except that the feedstock contains only CO_2 and H_2. Although the catalysts require some more development in terms of conversion, the process is gaining in interest due to rising environmental concerns and CO_2 taxes.
The energy demand of the conventional process via syngas is mainly thermal and about 1.71 kWh/kg of Methanol.[146] The required electricity is produced with the excess heat. The CO_2-based process however can be operated solely with electricity while the heat demand is covered with the exothermic reactions. If a reaction pressure of 80 bar is chosen, the total electricity demand is about 0.28 kWh/kg of Methanol, excluding the demand for H_2 production.[146]

Looking at commercial plants, Carbon Recycling International (CRI) is currently building a 330 t/d plant for CO_2 hydrogenation in China and plans to operate it end of 2021.[147] Therefore, an advanced TRL level of 8–9 can be assumed for this pathway. According to CRI, the production can be profitable without CO_2 taxes or subsidies, for a plant in China where H_2 from coke oven gas is considered together with CO_2 from a lime kiln. For such a case, costs were estimated at 255 EUR/t[148], while Siemens AG estimates a cost of 650–850 EUR/t[149] with renewable hydrogen. Thus, the main cost component for a renewable production is the cost of renewable hydrogen. While the CO_2-based production is mainly OPEX intensive, the conventional plant is CAPEX intensive.[150]

6.2.4 Formic Acid

In the past, formic acid was also obtained as by-product of acetic acid production. However, that changed when the carbonylation of methanol for acetic acid production became the preferred process. Nowadays, the conventional production of formic acid is mainly based on the hydrolysis of methyl formate. This process consists of two stages: In the first stage, the carbonylation of methanol with carbon monoxide yields methyl formate which is hydrolyzed in the second stage to formic acid and methanol. Other formic acid production paths include the oxidation of hydrocarbons, the hydrolysis of formamide, and via the preparation of free formic acid from formates. In the last decades, several options to produce formic acid based on carbon dioxide have been developed, however, not to a commercial scale so far.

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[145] Air Liquide, https://www.engineering-airliquide.com/de/lurgi-megamethanol, accessed 22.09.2021
[146] A. Otto, 2015, Chemical, Procedural and Economical Evaluation of Carbon Dioxide as Feedstock in the Chemical Industry, Energy & Environment
[147] CRI, https://www.carbonrecycling.is/technology, accessed 22.09.2021
[148] CRI presentation at 9th conference on CO_2-based fuels and chemicals, nova institute, 23.03.2021
[149] Presentation Siemens AG on ETIP Wind workshop 21.02.2019, “Electricity-based fuels as link between the electricity and transport sectors”
[150] Perez-Fortes et al., 2016, Methanol synthesis using captured CO_2 as raw material: Techno-economic and environmental assessment, Applied Energy

Electrochemical Route

Formic acid can be produced electrochemically of water and carbon dioxide according to the net reaction:

$$\mathrm{H_2O + CO_2 \rightarrow HCOOH + \frac{1}{2}\,O_2}\,,$$
$$\Delta H_{\mathrm{R}\,(T=298\ \mathrm{K})} = 254.26\frac{\mathrm{kJ}}{\mathrm{mol}}, \qquad \Delta G_{\mathrm{R}\,(T=298\ \mathrm{K})} = 269\frac{\mathrm{kJ}}{\mathrm{mol}}.$$

Under ideal conditions pure formic acid is formed at the cathode and O_2 at the anode.[151] However, one parasitic side reaction is the reduction of H_2O to H_2 and OH^- at the cathode, which reduces the faradaic efficiency to formic acid. The product distribution depends to a great extent on the selected catalyst and the reaction conditions. So far, tin, lead, bismuth, indium, mercury, and cadmium are known catalysts for electrochemical formic acid production.[152]

One crucial criterion for successful electrochemical formic acid formation is to overcome the low solubility of CO_2 in water. The CO_2 needs to be sufficiently dissolved in the water, since otherwise higher reaction rates result in a depletion of CO_2 on the catalyst surface. This limits the maximal possible current density, which determines the reactor size and thus capital cost.[153] For industrial applications a current density of at least 200 mA/cm² should be demonstrated for sufficiently high yields regarding space and time.[154] To tackle this, two concepts are currently investigated: Firstly, by using an aqueous solution with a solvent in a gas diffusion electrode. The gas diffusion electrode allows an intensive contact between gaseous CO_2, liquid electrolyte, and the solid electrode at an enlarged reaction surface relative to the geometrical surface. Secondly, supercritical CO_2 is used where the CO_2 acts as a solvent itself. This approach leads to higher CO_2 concentrations than in aqueous solutions at the cathode, but is not as developed as the aqueous solution approach with a reported current density of only 30 mA/cm² with a CO_2 pressure of 50 bar.[155,156]

A process flow sheet for the electrochemical reduction of CO_2 to formic acid is given in Figure 6-4. The most energy-intense step is the electrochemical reduction of CO_2 to formic acid in the electrochemical reactor. Under ideal conditions, i.e. no overpotential losses, no co-products and a maximum Faradaic Efficiency of 100%, the electrochemical process requires 1.75 kWh/kg formic acid (85% solution). However, taking into account a more realistic case with a Faradaic Efficiency of 42% and the co-production of H_2 and O_2, the energy demand rises to 11.8 kWh/kg formic acid solution.[151] The azeotropic mixture of

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[151] Rumayor et al., 2019, A techno-economic evaluation approach to the electrochemical reduction of CO2 for formic acid manufacture, Journal of CO_2 Utilization

[152] Final report, EnElMi 2.0, 2020, Energieeffiziente Elektrochemie im Mikroreaktor, University of Stuttgart, German Aerospace Center, PLINKE GmbH, funded by BMWI

[153] Whipple and Kenis, 2010, Prospects of CO2 Utilization via Direct Heterogeneous Electrochemical Reduction, The Journal of Physical Chemistry Letters

[154] Dufek et al., 2011, Bench-scale electrochemical system for generation of CO and syn-gas, Journal of Applied Electrochemistry

[155] Thonemann and Schulte, 2019, From Laboratory to Industrial Scale: A Prospective LCA for Electrochemical Reduction of CO2 to Formic Acid, Environmental Science & Technology

[156] Ramdin et al., 2019, High-Pressure Electrochemical Reduction of CO2 to Formic Acid/Formate: Effect of pH on the Downstream Separation Process and Economics, Industrial & Engineering Chemistry Research

formic acid and water is distilled to gain a product with 85% formic acid concentration, which is the industrial standard. By-products are H_2 and O_2, which are compressed into a liquid form.

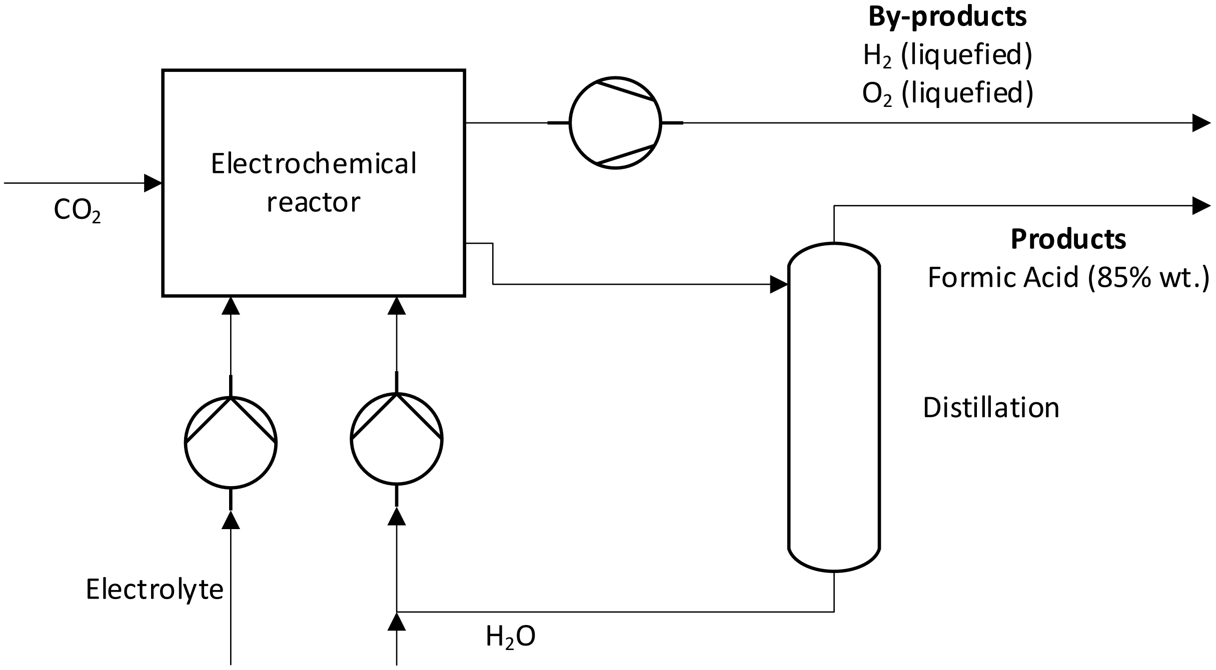

Figure 6-4: Flowsheet of electrochemical formic acid production (based on Rumayor et al. 2019[151]).

Several startups have been active in the field of electrochemical formic acid. Det Norske Veritas built a demonstration reactor converting 1 kg CO_2/day into formic acid (350 kg formic acid/year). The device was powered by PV electricity and consisted of 600 cm^2 of electrodes with electrodeposited Sn as catalyst. Mantra Venture Group constructed a pilot plant with a capacity to convert 100 kg CO_2/day (35 t formic acid/year) in 2013 at the Lafarge cement plant in Richmond, British Columbia, Canada.[157] However, no further development has been communicated since then. More recently, Coval energy BV and Twence announced the development of a pilot plant in Hengelo, Netherlands to commercialize the electrochemical formic acid production.[158] Also, Avantium plans to scale-up its Volta Technology, which is an electrocatalytic platform to reduce CO_2 to chemicals such as formic acid.[159] In addition, several EU projects and innovation actions aim to advance the electrochemical formic acid production to TRL 6, e.g., spire2030[160], VIVALDI[161], ConsenCUS[162], and recodeh2020[163].

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[157] https://finance.yahoo.com/news/mantra-announces-advancements-novel-fuel-141500379.html, accessed 22.09.2021

[158] https://www.voltachem.com/news/pilot-for-synthesis-of-formic-acid-from-co2-at-twence-waste-incineration-site, accessed 23.09.2021

[159] https://www.avantium.com/press-releases/avantium-awarded-e178-million-in-total-from-eu-grants-for-the-development-of-electrochemical-processes-and-co2-based-polymers/, accessed 23.09.2021

[160] https://www.spire2030.eu/ocean#edit-group_objetives, accessed 23.09.2021

[161] https://cordis.europa.eu/project/id/101000441/es, accessed 23.09.2021

[162] https://cordis.europa.eu/project/id/101022484, accessed 23.09.2021

[163] https://recodeh2020.eu/project, accessed 23.09.2021

As a conclusion, major challenges need to be tackled for an industrial application. The energy consumption needs to be reduced not only for the reactor but also for the associated separation process of the azeotrope of water and formic acid. [151] The consumable demand of electrolytes and electrodes needs to decrease, which is directly influenced by the durability of the cathode. A scale-up of the electrochemical reactor needs to prove sufficient effective mass transfer at the membrane under higher current densities[151] and inhibit the formation of competitive products, electrode decomposition and reoxidation.[155]

Hydrogenation Route

The hydrogenation of CO_2 yields formic acid according to

$$\mathrm{H_2 + CO_2 \rightarrow HCOOH,}$$
$$\Delta H_{\mathrm{R}\ (T=298\ \mathrm{K})} = -31.21\,\frac{\mathrm{kJ}}{\mathrm{mol}}.$$

The reaction is favored at high pressures and low temperatures. As the reaction is highly endergonic, solvents are required to alter the thermodynamics of the reaction. Polar aprotic solvents can enhance the activity of the catalyst and promote the reaction due to the solvation of the product.[146] In addition, bases (e.g. amines) increase the conversion rate according to[164]

$$\mathrm{H_2 + CO_2 + NH_{3\,(aq.)} \rightarrow HCO^-_{2\,(aq.)} + NH^+_{4\,(aq.)}}\,,$$
$$\Delta H_{\mathrm{R\ (T=298\ K)}} = 84.3\,\frac{\mathrm{kJ}}{\mathrm{mol}}.$$

and make the reaction exergonic. A common approach is esterification, e.g., reacting formic acid or formates with methanol to methyl formate, using primary or secondary amines to form formamides, or neutralize with tertiary amines or alkali/alkaline earth bicarbonates as weak base.[165] Depending on the amine, formic acid salt is formed or an azeotrope of formic acid and formic acid salts. Several catalysts (homogeneous and heterogenous), amines and solvents are under investigation, which result in reaction temperatures ranging from 25 °C to 240 °C and pressures of 2 to 205 bar.[164] The flowsheet in Figure 6-5 illustrates one exemplary approach of the CO_2 hydrogenation process yielding a formic acid solution with 85% concentration, which is based on a patent by BASF SE.[166,167] Both educts are initially compressed to 105 bar and then mixed in a reaction stage with a tertiary amine i.e. trihexylamine, and a mixture of methanol and water acting as a polar solvent in the presence of catalysts to form a formic acid amine. In a next step, liquid-liquid separation is performed to recover the ruthenium- and phosphino-based catalysts. The methanol recovery is achieved in a stripping column and a flow containing methanol, water and dissolved CO_2 is recycled to the reaction stage. In the last step the formic acid amine is thermally treated in a distillation stage for the formation and purification of formic acid. In the end, this process

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[164] Leitner, W., Carbon Dioxide as a Raw Material: The Synthesis of Formic Acid and Its Derivatives from CO2. Angewandte Chemie International Edition in English, 1995. 34(20): p. 2207-2221

[165] Alvarez et al., 2017, Challenges in the Greener Production of Formates/Formic Acid, Methanol, and DME by heterogeneously Catalyzed CO_2 Hydrogenation Processes, Chemical Reviews

[166] Pérez-Fortes et al., 2016, Formic acid synthesis using CO2 as raw material: Techno-economic and environmental evaluation and market potential, International Journal of Hydrogen Energy

[167] BASF SE, 2014, Process for preparing formic acid by reaction of carbon dioxide with hydrogen, Patent US8791297 B2

would require an electricity demand of 4 kWh/kg formic acid solution including the electrolysis step for H_2 provision.

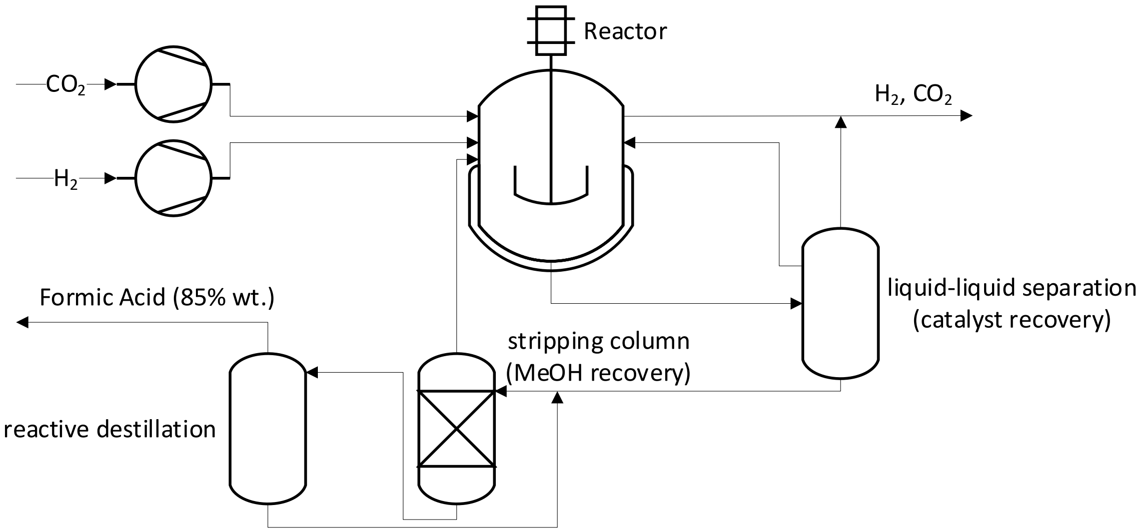

Figure 6-5: Flowsheet for the hydrogenation of CO_2 to formic acid (simplified from Perez-Fortes et al. 2016[166]).

One major challenge for the commercialization of the CO_2 hydrogenation technology is related to the difficulty of extracting formic acid from the salts or azeotrope, while still recycling the catalyst and base. Furthermore, the salts or azeotrope easily decompose in presence of the catalyst under thermal treatment and form H_2 and CO_2.[168,164] Different approaches have been presented to tackle the difficult extraction of formic acid of the product mix: Firstly, British Petroleum patented a process in the 1980s, which is based on the amine exchange between the formates or azeotropes and high-boiling amines.[169] A second approach makes use of a multi-phase reaction system, which results in simpler separation of the catalyst and the reaction product due to the different phases.[170] This is also applied by BASF SE using trihexylamine as base and a ruthenium-based catalysts as described in Figure 6-5.[171,172] In addition, a process using water and a solid ruthenium-based catalyst enabled the filtration of the catalyst after the reaction and is reported to be less energy-intensive, however, working at higher pressures of 150 bar. [164,159, 173] Finally, a process combining the hydration of CO_2 and the separation of formic acid in one step was proposed by RWTH Aachen. This can be achieved by applying supercritical CO_2 as mobile phase and an ionic liquid as stationary phase, which consists of a ruthenium-based catalyst and a base, at reaction conditions of 60 °C and 200 bar. However, the recirculation of the supercritical CO_2 and its

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[168] Zhang et al., 2008, Hydrogenation of Carbon Dioxide is Promoted by a Task-Specific Ionic Liquid. Angewandte Chemie

[169] Behr and Nowakowski, 2014, Catalytic Hydrogenation of Carbon Dioxide to Formic Acid CO2 Chemistry, Advances in Inorganic Chemistry

[170] BP Chemicals Limited, 1989, Process for the Preparation of Formic Acid, WO86/02066

[171] BASF SE, 2010, Verfahren zur Herstellung von Ameisensäure, WO2010/149507A2.

[172] Schaub and Paciello, 2011, A Process for the Synthesis of Formic Acid by CO_2 Hydrogenation: Thermodynamic Aspects and the Role of CO. Angewandte Chemie International Edition

[173] Zhang et al., 2009, Hydrogenation of CO2 to Formic Acid Promoted by a Diamine Functionalized Ionic Liquid, ChemSusChem

separation from formic acid is limiting this approach. [174,175] A second obstacle for commercialization is the catalyst price and catalyst demand of the above presented CO_2 hydrogenation approach demanding either a process optimization or development of different catalysts.[166]

So far, no process prevailed due to the respective advantages and disadvantages. Either the operational pressure of the process is relatively low, but it requires a complex treatment of intermediates and the catalyst (BP, BASF SE, Behr and Nowakowski[169]), or the extraction of formic acid is simplified, but the process works at relatively high pressures of 180 to 200 bar and/or necessitates the energy-intensive recycling of high amounts of CO_2 (Zhang et. al[168], RWTH Aachen[174]). Currently, project CO2PERAT plans the development of four catalytic synthesis routes for formic acid based on CO_2, one of them being homogenous and heterogenous catalysis for the hydrogenation of CO_2[176]. Furthermore, researchers investigated the coupling of CO_2 capture and CO_2 hydrogenation to formate salts, which shall omit the energy-intensive desorption and compression steps.[177]

6.3 Comparison of Potential Concepts

The CCU options selected for concept development - described in chapter 6.2 - were compared from three points of view: technological, economical and local aspects for the chosen chemical site of Knapsack.

Technological Aspects

The detailed technical description of the two selected CO_2-based chemicals - acetic acid and formic acid - are described in chapter 6.2. One major difference is the TRL: Acetic acid can be produced by a state-of-the-art facility, but requires CO_2-based methanol and/or carbon monoxide to become CO_2-based acetic acid. In this case one option could be to build a commercial-scale acetic acid plant and to ramp-up the CO_2-based feedstock over time, either by on-site production or by green methanol imports. The TRL of CO_2-based methanol production is rather high, and demo-scale projects could be easily deployed on-site. CO_2-based carbon monoxide is also at demo scale (TRL 8)[132], but targeting smaller production units than potentially required for acetic acid production. Thus, a combination of more CO_2 reduction modules is required to satisfy the demand. But this should be compared to an assessment of other sustainable feedstocks for carbon monoxide production, which is not part of this study.

Both formic acid production options are still on lower TRL and the next step would be a pilot scale facility to further develop the technologies. As outlined in chapter 6.2, many hurdles need to be resolved to achieve a commercial ready process.

At the end, it depends on the timeline and envisioned scale of CCU application on the chemical site, which chemical would be the best fit. Formic acid allows for smaller piloting projects, which might be eligible for public funding. Additionally, upcoming changes in regulation or incentive schemes might become clearer

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[174] Rheinisch-Westfaelische Technische Hochschule Aachen, Germany, 2012, Continuous process for production of formic acid by hydrogenation of carbon dioxide and extraction of formic acid by compressed CO_2, WO2012095345A1

[175] Wesselbaum, S., U. Hintermair, and W. Leitner, Continuous-Flow Hydrogenation of Carbon Dioxide to Pure Formic Acid using an Integrated scCO2 Process with Immobilized Catalyst and Base. Angewandte Chemie International Edition, 2012. 51(34): p. 8585-8588.

[176] https://catalisti.be/project/co2perate/, accessed 23.09.2021

[177] https://pubs.acs.org/doi/10.1021/acs.accounts.9b00324, accessed 23.09.2021

by the time these technologies reach commercial maturity. On the other hand, the acetic acid case could start with a conventional full-scale plant, and depending on economic or other motivation, the feedstock can gradually be replaced by CO_2-based feedstocks or other sustainable feedstock options. The flexibility in feedstock (conventional, CO_2-based or other sustainable sources) has the benefit to react more variable on changes in the market, regulations or other impacting factors.

Economic Aspects

The basis for the economical evaluation is the cost of production using a bottom-up approach. Publicly available information has been used to model equipment and personnel costs together with common engineering design factors for each process, which are described in sections 6.2.2, 6.2.3 and 6.2.4. Overall, four processes have been analyzed: acetic acid, methanol, formic acid (hydrogenation) and formic acid (electrochemical). Additionally, the cost of carbon capture from a waste to energy plant was estimated (see section 6.2.1).

The net present value (NPV) calculation is used to assess the economic viability from an investors point of view. Common financial factors have been used and are summarized in the following table.

Table 6-2: Economic parameters used for NPV calculations.

Economic Parameters	
Depreciation, years, straight line[178]	20
Inflation[179]	1.7%
Tax rate[180]	30%
Discount rate (WACC)[178]	10%

As the economic assessment in this study is based on rather general information, three scenarios were used for NPV calculations: a base scenario considering the current market price and cost estimates as outlined in part B and additionally a pessimistic and an optimistic scenario to reflect on potential market fluctuations (Table 6-3). In case of energy and hydrogen cost respectively, a reduced cost rate was used in the base scenario compared to Part B, to reflect lower surcharges on the energy prices, which might be applicable at a large industrial or chemical site. To identify the main cost drivers of the individual processes, single variables were modified from the base scenario. At this point, one needs to bear in mind, that this economic assessment is rather simplified and its goal is to compare different technologies using similar cost assumptions.

The production volume of the plants was categorized in two cases: site demand and site CO_2. For the site demand case, the production volume is equal to the demand of the chemical within the chemical park. The site CO_2 case has a production volume, which utilizes the entire CO_2 available from the waste to energy plant. At this stage, the conventional acetic acid plant is considered, meaning using fossil feedstocks only. The size of the acetic acid plant in the “site CO_2” case is based on the methanol amount, which would be

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[178] Friedmann et al., 2020, Capturing investment: policy design to finance CCUS projects in the US power sector

[179] https://www.wirtschaftsdienst.eu/inhalt/jahr/2020/heft/11/beitrag/ein-hoeheres-inflationsziel-fuer-die-ezb.html, accessed 22.09.2021

[180] https://bericht.basf.com/2020/de/konzernabschluss/anhang/erlaeuterungen-zur-guv/ertragsteuern.html, accessed 22.09.2021

produced using the CO_2 available at site. The use of CO_2-based methanol as feedstock will be discussed at a later point. Hence the plant capacities considered are 23 kt/a to 513 kt/a for acetic acid and 3 kt/a and 350 kt/a for formic acid production.

Table 6-3: Input parameters for economic assessment for the three different scenarios. Assumptions for optimistic and pessimistic scenarios are based on market price ranges and range of CAPEX estimates, respectively.

Parameter	Unit	Optimistic		Base	Pessimistic	
Carbon Monoxide (CO)	EUR/t	250	- 29%	350	450	+ 29%
Methanol (fossil)	EUR/t	225	- 38%	360	450	+ 25%
Methanol (green / CO_2-based)	EUR/t	820	+ 12%	735	625	- 12%
Carbon Dioxide (CO_2)	EUR/t	54	- 40%	90	126	+ 40%
Electricity	EUR/MWh	37.4	- 45%	68.1	92	+ 35%
Heat	EUR/MWh	15.8	- 45%	28.9	39	+ 35%
Hydrogen (H_2) – energy demand	kWh/kg	54		54	54	
Hydrogen (H_2) – cost based on energy price	EUR/t	2,017	- 45%	3,676	4,968	+ 35%
Acetic Acid price (conventional)	EUR/t	625	+ 25%	500	375	- 25%
Formic Acid price (conventional)	EUR/t	846	+ 25%	677	508	- 25%

Realistic energy demands were considered for the different processes as described in chapter 6.2 in order to avoid over ambitioned outcomes. As expected, the results of the NPV calculation (Table 6-4) show that the incentive for realizing a CO_2-based chemical production is not economically driven as long as no regulation or incentive scheme is in place to support sustainable chemical production. For the formic acid (hydrogenation) all NPVs are negative, and for conventional acetic acid and CO_2-based methanol all NPVs besides the optimistic scenario (site CO_2) are negative. The NPVs of formic acid (electrochemical) were only positive for the two optimistic scenarios (site demand & site CO_2) and the base scenario (site CO_2).

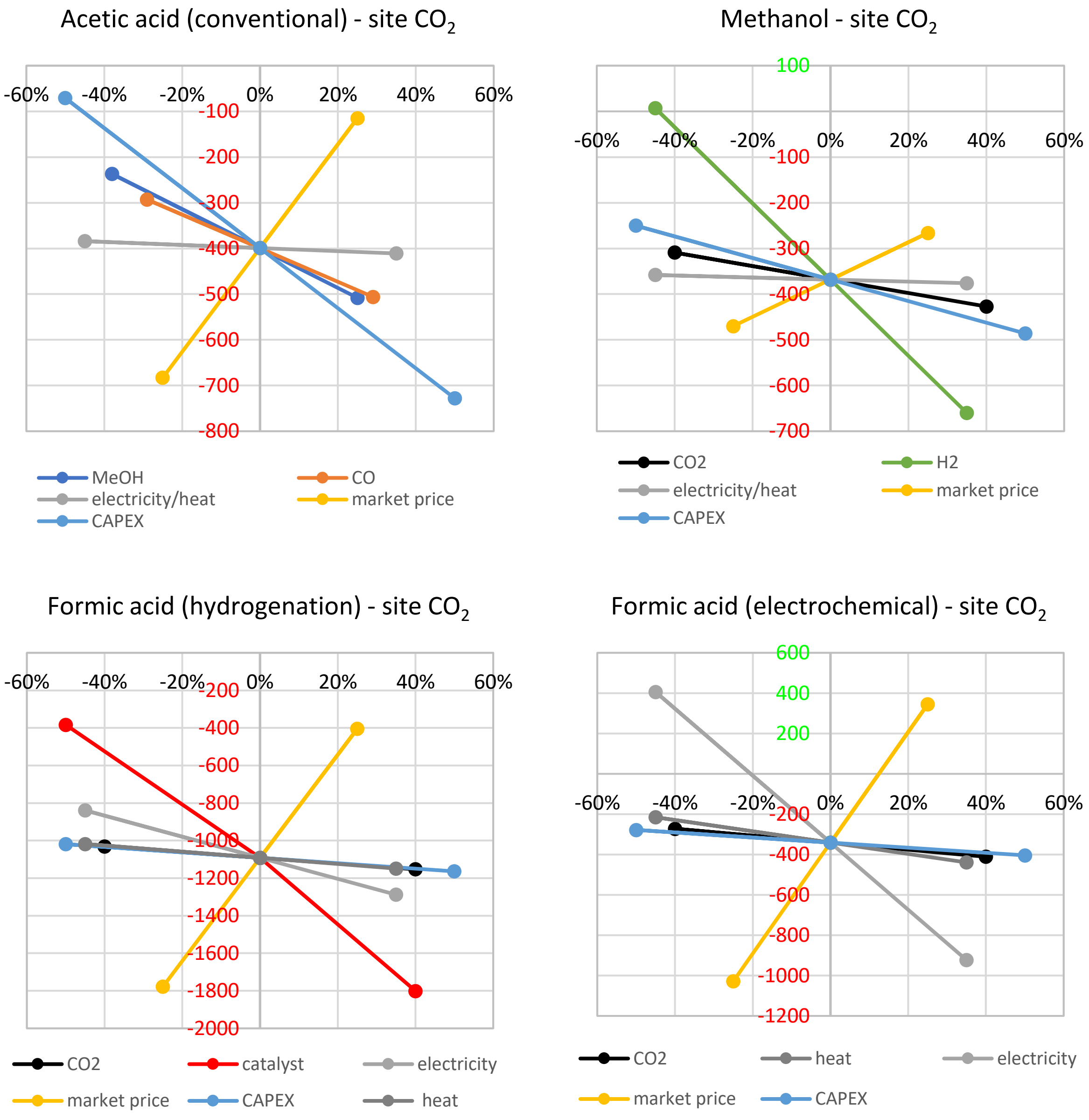
Since a conventional process was considered for acetic acid production, which is feasible from a global perspective, it has to be assumed that either the used cost assumptions are too conservative, since economic feasibility (NPV >0) is only achieved in the optimistic case or that acetic acid production requires locations with respective lower cost structure.

Table 6-4: Results of NPV calculation: Case 1 = local demand of chemical (small plant), Case 2 = production volume based on local CO_2 supply (large plant). NPV of acetic acid is based on conventional feedstock supply.

NPV [Mio EUR]	Acetic Acid (conventional)		Methanol CO_2-based		Formic Acid Hydrogenation		Formic Acid Electrochemical	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Optimistic Case	-50	169	-15	179	-28	-362	5	1,392
Base Case	-125	-399	-68	-368	-34	-1,092	-7	106
Pessimistic Case	-174	-910	-112	-830	-40	-1,749	-17	-986

Avoiding the use of fossil carbon and transforming towards sustainable carbon sourcing, CO_2-based feedstock production is the main focus of this study. The motivation for the economic assessment was to identify the main cost driver in order to understand if and how such projects might become feasible.

Therefore, a sensitivity analysis was conducted. The starting point for this analysis was the base scenario of the "site CO_2" cases since larger-scale plants are more favorable from an economic point of view as will be shown later (see Figure 6-7). On this basis, one parameter was changed at a time to calculate the new NPV value. The varied values are based on the optimistic and pessimistic assumptions for costs and prices as shown in Table 6-3Table . For the CAPEX and catalyst cost (where applicable) a variation of 50% was chosen. The results of the analysis are shown in Figure 6-6.


Acetic acid (conventional) - site CO_2

Methanol - site CO_2

Formic acid (hydrogenation) - site CO_2

Formic acid (electrochemical) - site CO_2

Figure 6-6: NPV variation from base case for conventional acetic acid, CO_2-based methanol and formic acid (hydrogenation and electrochemical route) using the percentage change of optimistic and pessimistic variables for input/output flows.

The sensitivity analysis for acetic acid shows, that the CAPEX is the biggest cost driver, followed by the market price. Feedstock cost for methanol and CO have a moderate impact, while power/heat costs are rather negligible from an impact point of view. The costs for CO_2-based methanol production are mainly driven by the hydrogen feedstock cost. CAPEX and market price have a much lower but similar impact. The hydrogen demand for producing formic acid via hydrogenation is considered by including the required electricity consumed in the process. Despite the resulting high energy demand, the catalyst cost and the market price have the largest impact on the economic performance. Since this technology is at low TRL, advancements in catalyst development might be possible, which can greatly improve the overall economics. In case of electrochemical production of formic acid, the market price and electricity cost are the main impact factors. Similar to the hydrogenation route, further improvement of technology could improve the overall economics. Overall, the four assessed cases indicate different main cost drivers, which are summarized in Table 6-5.

Table 6-5: Main cost drivers identified by the sensitivity analysis.

Product	Main cost drivers
Acetic Acid (conventional)	CAPEX
Methanol (catalytic)	Hydrogen (ca. 76% of the OPEX)
Formic Acid (hydrogenation)	Catalysts (ca. 51% of the OPEX)
Formic Acid (electrochemical)	Electricity (ca. 64% of the OPEX)

Figure 6-7 shows potential scaling effects on the economics. The CAPEX and OPEX were divided by the plant capacity, showing the impact of these cost factors on a cost per product view. All options show that higher outputs are favorable for the economics. In almost all cases, an increase in plant capacity halved the capital investment contribution to production cost per ton. The increased plant capacity for formic acid (electrochemical) even led to a sharp decline in CAPEX from 1800 EUR/t to roughly 400 EUR/t, which is a decrease of 77%.

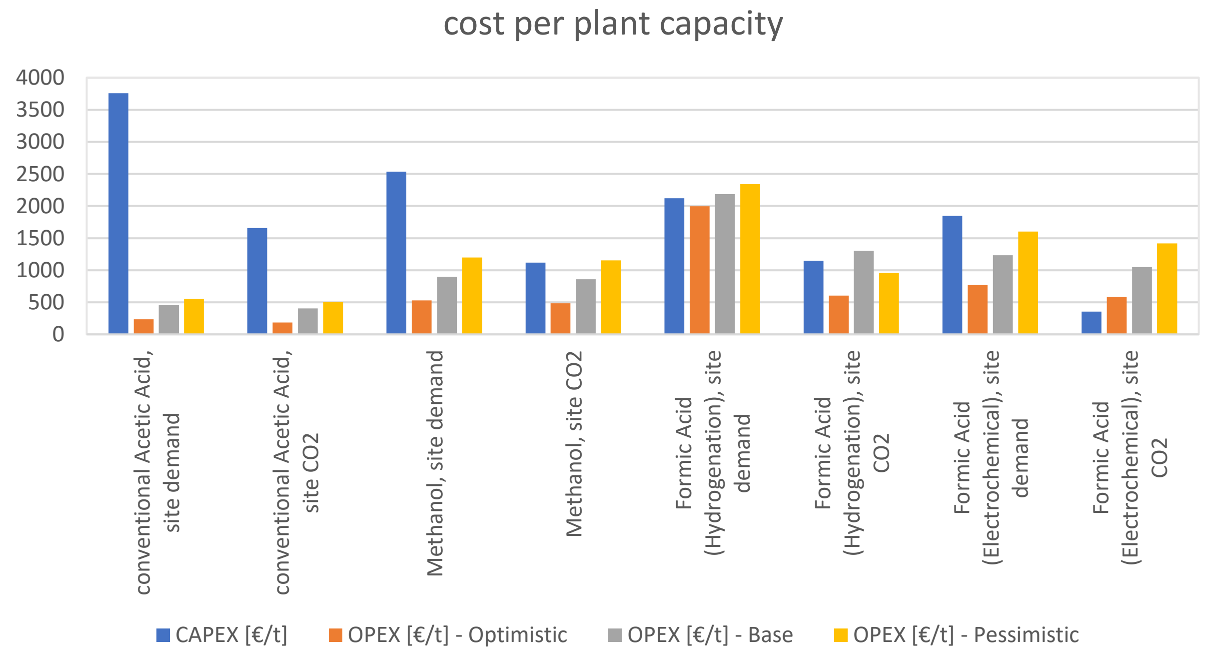


Figure 6-7: Cost per plant capacity considering the plant sizes for local demand of chemical (site demand) and chemical production based on available CO_2 (site CO_2). Conventional acetic acid plant parameters are shown and site CO_2 in this case is based on CO_2-based methanol volume. Methanol site demand is considering the amount needed for the local acetic acid supply.

It needs to be noted, that the scaling factor from “site demand” to “site CO_2” is not equal for acetic acid and formic acid due to different demand of the respective chemical within the chemical park. The acetic acid plant capacities are approx. 38 kt/a for the local demand case and about 390 kt/a for the “CO_2 site” case (scaling factor of 10). Both plant capacities are comparable to other European installations, which range from 23 kt/a to 513 kt/a capacity[181]. The formic acid plant capacities are approx. 3 kt/a and 350 kt/a (scaling factor of 117), respectively, while typical commercial installations have a capacity of 5 kt/a to 180 kt/a[182]. The uncertainties in scale-up of low TRL technologies like CO_2-based formic acid need to be kept in mind, especially when applying a scaling factor of 117 as used here.

The demand for a given chemical is another important factor for determining a reasonable plant capacity. The NRW demand for acetic acid was identified to be about 700 kt/a and for formic acid about 300 kt/a. Consequently, a plant capacity based on the CO_2 supply from the waste to energy plant would cover 57% of the acetic acid demand in NRW and oversupply the formic acid demand (122%).

Economic View on CO_2-based Methanol as Feedstock in Conventional Acetic Acid Plant

So far, the acetic acid plant economics were based on conventional feedstock, considering fossil-based methanol and carbon monoxide. As described earlier, a CO_2-based CO production appears not to be the best alternative pathway and other (e.g., waste or biomass-based) processes should be assessed in a separate study. Therefore, the focus in this study is on CO_2-based methanol production as feedstock for acetic acid production. For the economic assessment of this scenario the cost for CO_2-based methanol needs to be considered as feedstock cost within the acetic acid plant. As was shown above, the individual economics – conventional acetic acid plant and CO_2-based methanol plant – are not favorable in the base case scenarios.

To get a deeper understanding of the economics behind the processes as well as to understand what kind of subsidy is needed to make such a process feasible, the above used base scenarios were adapted. Two modified base case scenarios for the acetic acid production were evaluated, considering the “CO_2 on site” case. Starting from the base scenario the market price was increased by 25% and the CAPEX was reduced by 25%. This led to an NPV of 49 Mio EUR. The second new base case scenario was adjusted in the same manner, but with a decrease of 40% in CAPEX, increasing the NPV to 279 Mio EUR. The parameters for the two modified base cases are shown in Table 6-6.

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[181] https://www.icis.com/explore/resources/news/2017/12/14/10174370/chemical-profile-europe-acetic-acid/ accessed 23.09.2021

[182] Afshar A.A.N., TranTech Consultants Inc., 2014, Chemical Profile Formic Acid

Table 6-6: Parameters for the two modified base cases for acetic acid production considering the available CO_2 on-site for methanol production and results of target value analysis.

Acetic Acid – "CO_2 on Site" case		Base Case (CAPEX -25%)	Base Case (CAPEX -40%)
Input parameters			
Carbon Monoxide (CO)	EUR/t	350	350
Methanol (fossil)	EUR/t	360	360
Carbon Dioxide (CO_2)	EUR/t	90	90
Electricity	EUR/MWh	68.1	68.1
Heat	EUR/MWh	28.9	28.9
Hydrogen (H_2) – energy demand	kWh/kg	54.0	54.0
Hydrogen (H_2) – costs based on energy price	EUR/t	3676.3	3676.3
Market price acetic acid (+25% compared to initial base case)	EUR/t	625	625
CAPEX		75% of base scenario	60% of base scenario
Results of target value analysis (NPV acetic acid equal to zero)			
Maximum methanol price	EUR/t	400.5	591.7

Further, a target value analysis was conducted to calculate the highest methanol price, which would still result in a NPV equal to zero. This calculation showed that a methanol price of 400.5 EUR/t, 591.7 EUR/t respectively would result in a neutral NPV. No subsidies or green premium for CO_2-based consumables were considered at this stage. These methanol prices are still below current estimates for CO_2-based methanol ranging from 650 EUR/t to 850 EUR/t[149], but it indicates, that higher feedstock costs for sustainable chemical production might be eased either by subsidies for capital investments and / or by regulations supporting higher market prices for respective products. Since the discussion about subsidies and regulatory aspects is very complex and several options are conceivable, the determined methanol costs from the modified acetic acid cost modelling were used to identify the impact on methanol production economics. As expected, above methanol prices of 400.5 EUR/t and 591.7 EUR/t respectively, resulted in negative NPVs of -770 Mio EUR and -540 Mio EUR, respectively for the base case methanol plant. The main impact on this methanol price is the cost of hydrogen (see sensitivity analysis Figure 6-6), but the capital investment and market price have also a significant impact. Therefore, the methanol base case was adopted in a similar logic used for the acetic acid base case, but focusing on reducing the CAPEX, since the market price of the methanol is pre-determined from the acetic acid calculation. A reduction of 40% in CAPEX was assumed and as expected, the NPVs improved only slightly to -677 Mio EUR and -446 Mio EUR, respectively. In a last step, target value analysis was performed to identify under which hydrogen costs and which CO_2 costs such a methanol plant would become cost neutral. The results of this analysis are shown in Table 6-7.

Table 6-7: Correlation between CO_2 and hydrogen costs to achieve cost neutrality for the modified methanol base case (-40% CAPEX, market price methanol 591.7 EUR/t).

CO_2 price [EUR/t]	H_2 price [EUR/t]
-181	3,676
0	2,358
50	1,994
75	1,812
100	1,630

With the currently assumed hydrogen base price of 3,676 EUR/t, the CO_2 feedstock would come with a cost penalty of -181 EUR/t. At zero costs for CO_2, the hydrogen price would need to be reduced to 2,358 EUR/t, which might be achievable in the mid-term future as outlined by the optimistic hydrogen costs used within the sensitivity analysis above.

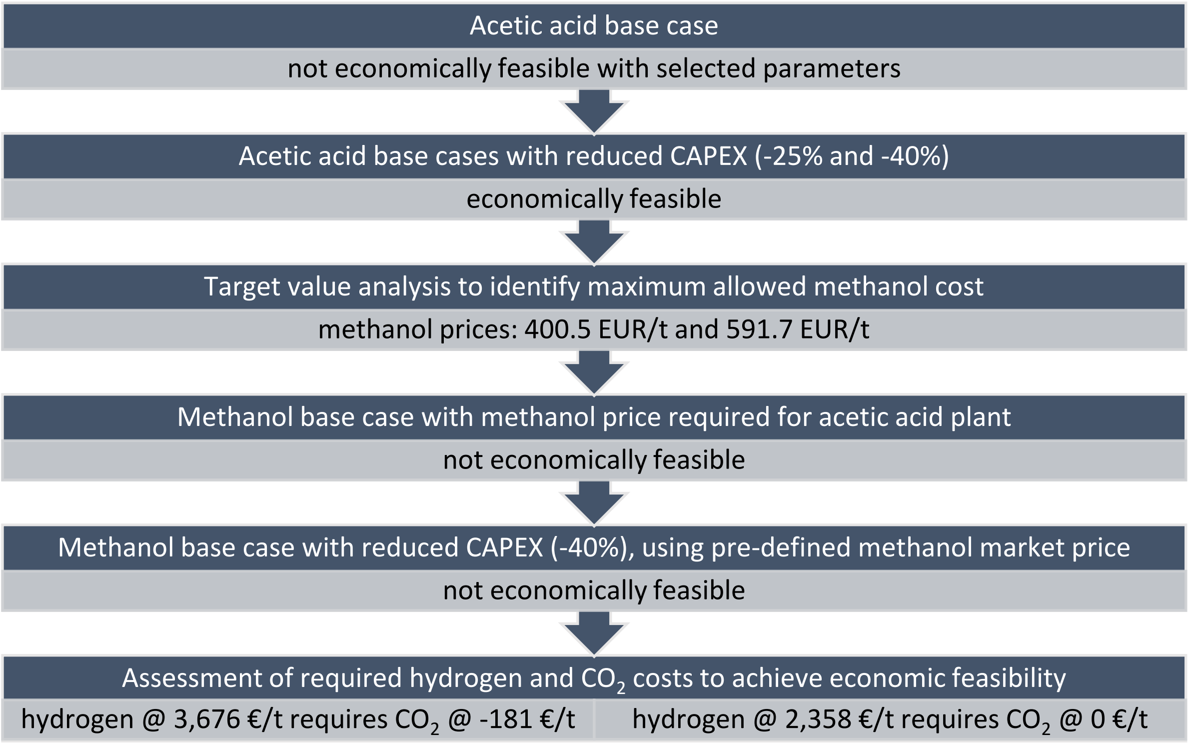

Figure 6-8: Flow scheme of economic assessments and modifications to base cases for acetic acid and methanol production plants in order to assess economic feasibility possibility, e.g., NPV = 0.

CO_2 Avoidance Cost

In view of climate change, the need to avoid CO_2 emissions is obvious and often the main question is about the cost for CO_2 avoidance. Different approaches are possible to calculate these costs. In this study, the results of the NPV calculations were used and combined with the identified carbon footprint of the respective chemical compared to the conventional process for the future scenario (carbon footprint reduction potential). For the different base case scenarios discussed above for CO_2-based acetic acid, the CO_2 avoidance cost ranges from 144 EUR to 249 EUR per ton of CO_2 avoided. For formic acid, the CO_2 avoidance cost in the base case scenario for the larger plant is 89 EUR/tCO_2 for the hydrogenation pathway, while the electrochemical pathways had a neutral / minimal positive NPV. The cost for CO_2 capture was included in the NPV calculations.

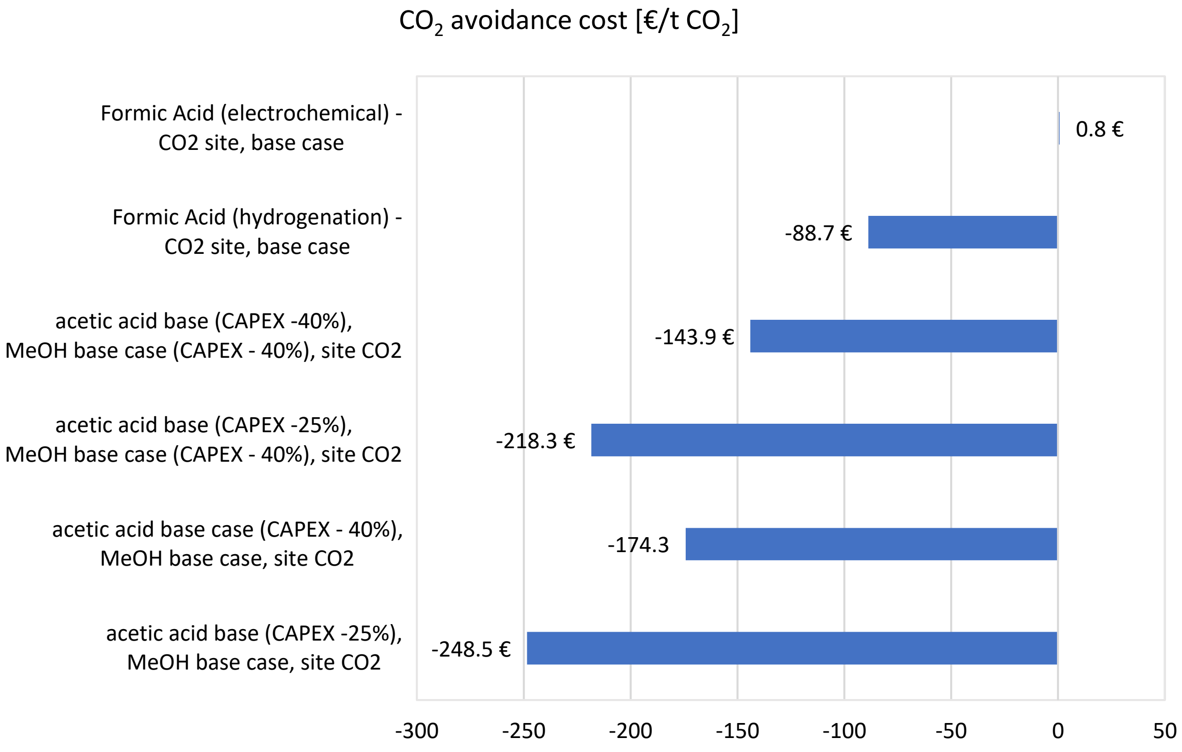

Figure 6-9: CO_2 avoidance costs based on NPV calculation and carbon footprint reduction potential (future scenario).

As an outlook: lower hydrogen costs would reduce the CO_2 avoidance costs. Deeper economic assessments are required and recommended to identify possibilities and limitations considering potential future regulations for this set-up.

Local Aspects

Several aspects need to be considered, when assessing a site for a new plant or plant addition. Basic conditions are space / land availability and access to required utilities like electricity, heat and water. From an investors' point of view, the economics are essential, while a site developer will be looking into what kind of business should be added to an existing site and if there are potential upsides like increase in public acceptance, interactions with existing customers and many more. The economics have been discussed earlier and the pre-selection of chemicals considered already, which products might be used within the chemical park. Therefore, this section will focus on the basic site demand factors.

At Knapsack chemical park, about 160 ha of expansion area is foreseen, which is more than sufficient space for the described CCU concepts, even including the required electrolyzer units (Figure 6-10).

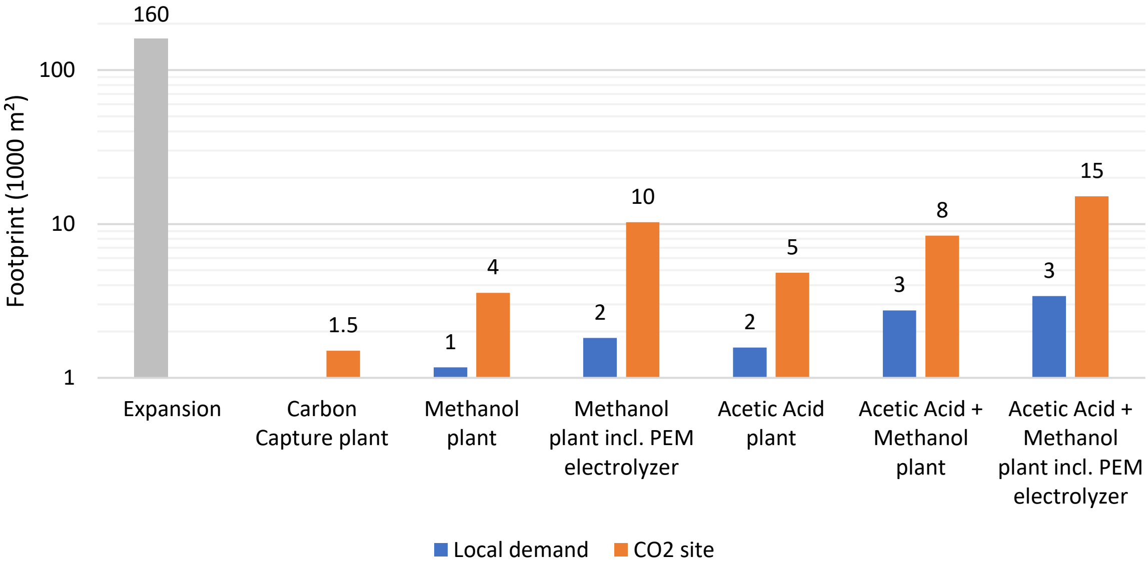

Figure 6-10: Footprint of different plant options compared to available expansion area. The plant sizes are based on common values.

For new plants, the exact location of available space is less critical. However, a carbon capture plant should be located close to the CO_2 point source. Based on the anticipated CO_2 capture capacity of about 290 kt/a, a footprint of approximately 25 m x 60 m can be assumed as a first estimate.[137,183] A bird's view shows, that some free space is available in close proximity to the waste-to-energy plant. The location for the carbon capture plant shown in Figure has a distance of about 190 m to the WtE plant, which is not optimal in view of required flue gas piping. A more detailed assessment is required to identify the best location for such a plant and to potentially reduce the distance. From a general perspective, it appears to be feasible to retrofit a carbon capture plant at this site.

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[183] https://akercarboncapture.com/offerings/just-catch/, accessed 23.09.2021

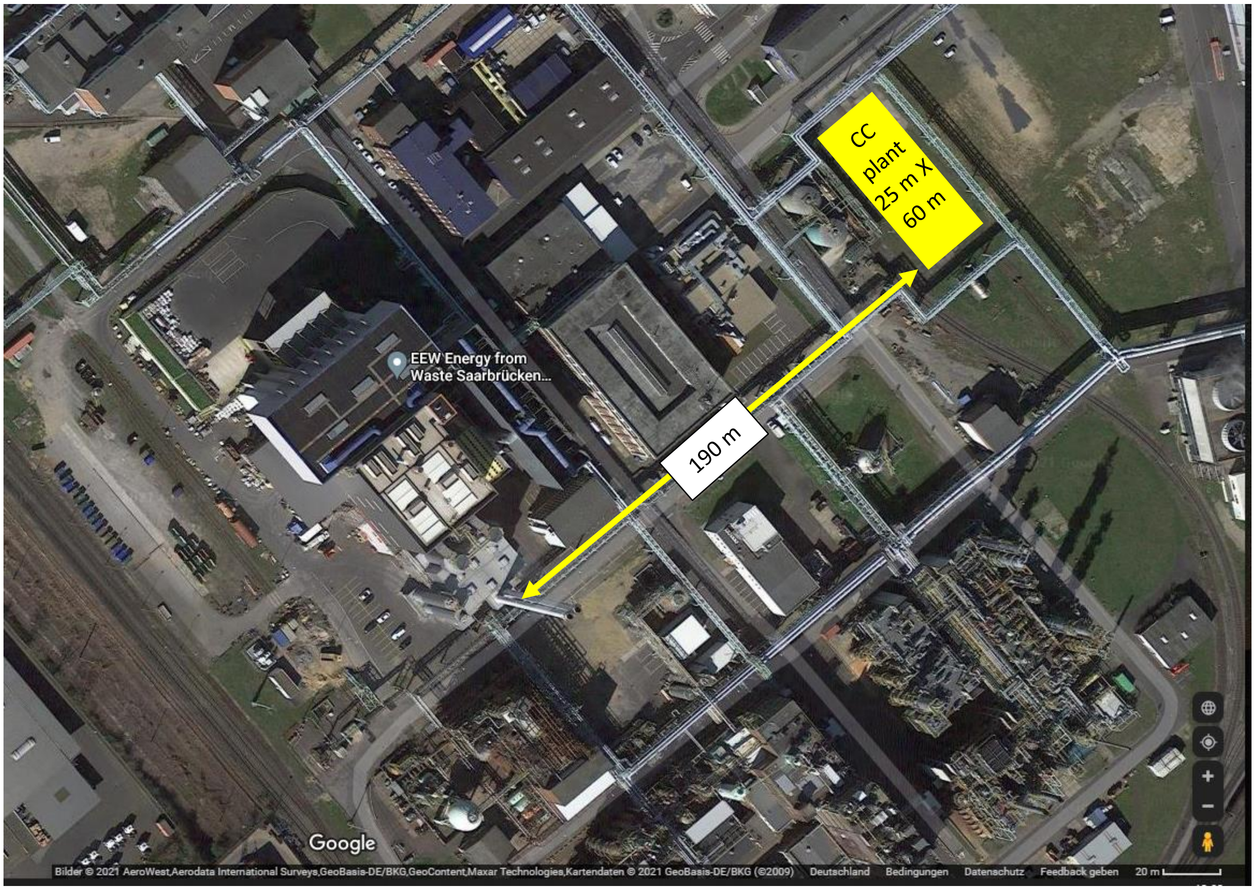
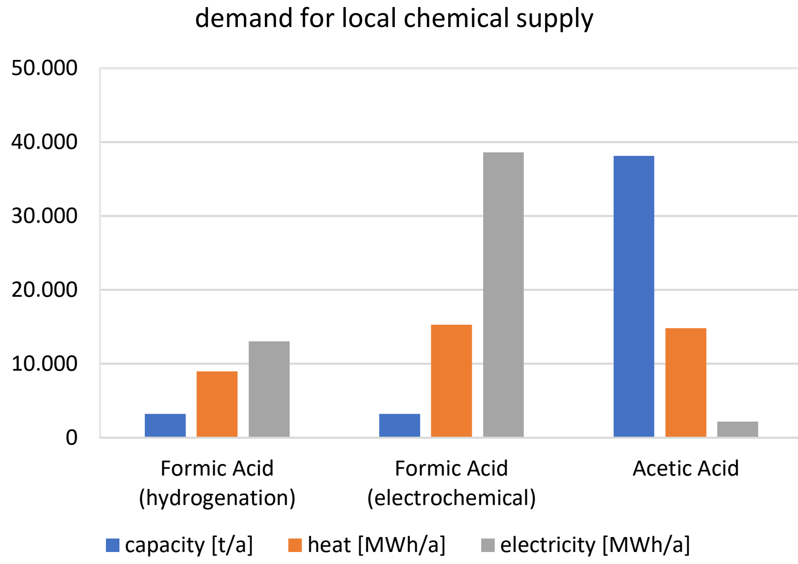


Figure 6-11: Satellite view on eew from Waste Saarbrücken, source Google Maps, copyright AeroWest, Aerodate InternationalSurvey, GeoBasis-DE/BKG, GeoContent Maxar Technologies, Kartendaten ©2021 GeoBasis-DE/BKG (© 2009).

Another critical factor is the energy demand for the different plants. The required heat and electricity for the considered plant options, e.g., acetic acid, formic acid, methanol and carbon capture, are shown in Figure 6-12.

The required heat demand for a carbon capture plant is in line with other facilities located within the chemical site at Knapsack and supply is not considered critical. Potential electricity demand of 3 MW for CO_2 compression and liquefaction, if required, should be in line with existing capacities as well.

The different CCU options however, require a significant amount of additional electricity, either for hydrogen production needed for methanol, formic acid production or for the electrochemical formic acid process. While the plain acetic acid plant has a rather low demand on electricity and a moderate demand for heat, the corresponding methanol synthesis would require about 40 to 50 MW electrical power (in case of local CO_2 supply case). The demand of the formic acid application based on realistic assumptions would be even higher. This amount of additional electrical capacity cannot be sourced from within the chemical park and would require system expansion and alignment with respective providers. Due to the required network expansion work, the overall cost for such a project would increase. An alternative for the high electrical energy demand in case of methanol production and formic acid production via hydrogenation could be the supply of hydrogen via a pipeline network. It might be a more strategic decision of the site developer if in future an access to a hydrogen pipeline is more beneficial than a network expansion, in order to deal with the electrification needs within the chemical industry.



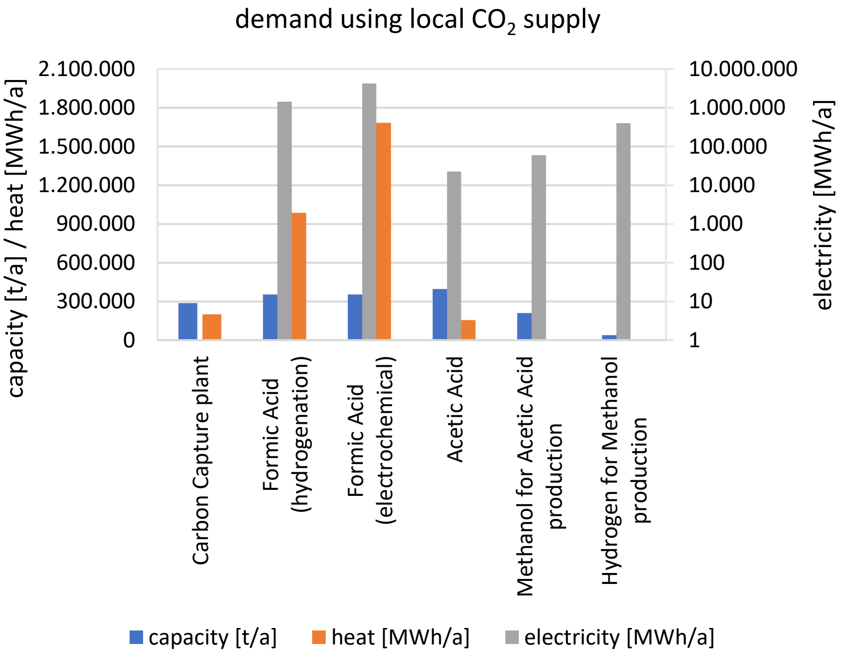


Figure 6-12: Demand for heat and electricity for the different CCU options, depending on plant capacity.

6.4 Concept Study: Summary and Conclusion

The techno-economic assessments show, that neither acetic acid via CO_2-based methanol nor CO_2-based formic acid are economically viable in the base scenario. With optimistic parameters, there might be a potential for the electrochemical formic acid production in future, pre-supposed that the technology develops further as anticipated. The hydrogenation route towards formic acid might become commercially attractive if major breakthroughs are achieved in respect to the catalyst cost. Even though CO_2-based methanol appears to become viable under the optimistic scenario it is assuming a higher market price for CO_2-based methanol (green premium) than for fossil methanol. It must be considered, that the acetic acid case is only economically viable when considering fossil-based feedstock with a very low methanol feedstock price. Therefore, it does not reflect a CO_2-based system in itself, but it also does not reflect a green premium for the acetic acid. In chapter 6.3, an integration of CO_2-based methanol into the acetic acid plant was discussed and respective cost allocations were made. On a side note, there is currently little to no acetic acid production within Germany and the major demand is imported. Therefore, advantages of local acetic acid production should be assessed further.

From a regulatory perspective, no incentive is yet in place to support CO_2-based chemicals as CCU options are not eligible carbon reduction measures under the ETS scheme. This might change in future, but cannot be foreseen. Other subsidies supporting capital investments in such technologies could contribute partially to achieve economic viability. However, additional release on aspects such as energy surcharges to reduce operational costs would still be required.

In view of climate change, the discussed chemicals would contribute to reduce GHG emissions. Based on the future scenario established in the study, CO_2-based acetic acid would have a CO_2 reduction potential between 0.4 to 1.4 kg CO_2 avoided per kg acetic acid when comparing to conventional acetic acid production. The range reflects that either only CO_2-based methanol would be used (0.4 kg CO_2 avoided / kg acetic acid) or CO_2-based methanol and CO_2-based carbon monoxide would be used (1.4 kg CO_2 avoided / kg acetic acid). The formic acid options would avoid about 1.7 to 1.8 kg CO_2 per kg formic acid compared to the conventional process. Considering the CO_2 avoided per product, formic acid has a larger impact than acetic acid. However, depending on the market demand, the total amounts produced differ significantly as the anticipated German market for acetic acid is more than double the volume of formic acid (about 700 kt/a versus 300 kt/a). The impact on GHG emissions savings for the chemical site assessed in the concept phase has even a broader variation, depending if the local chemical demand is met or if the CO_2 emission from the local waste to energy plant is converted.

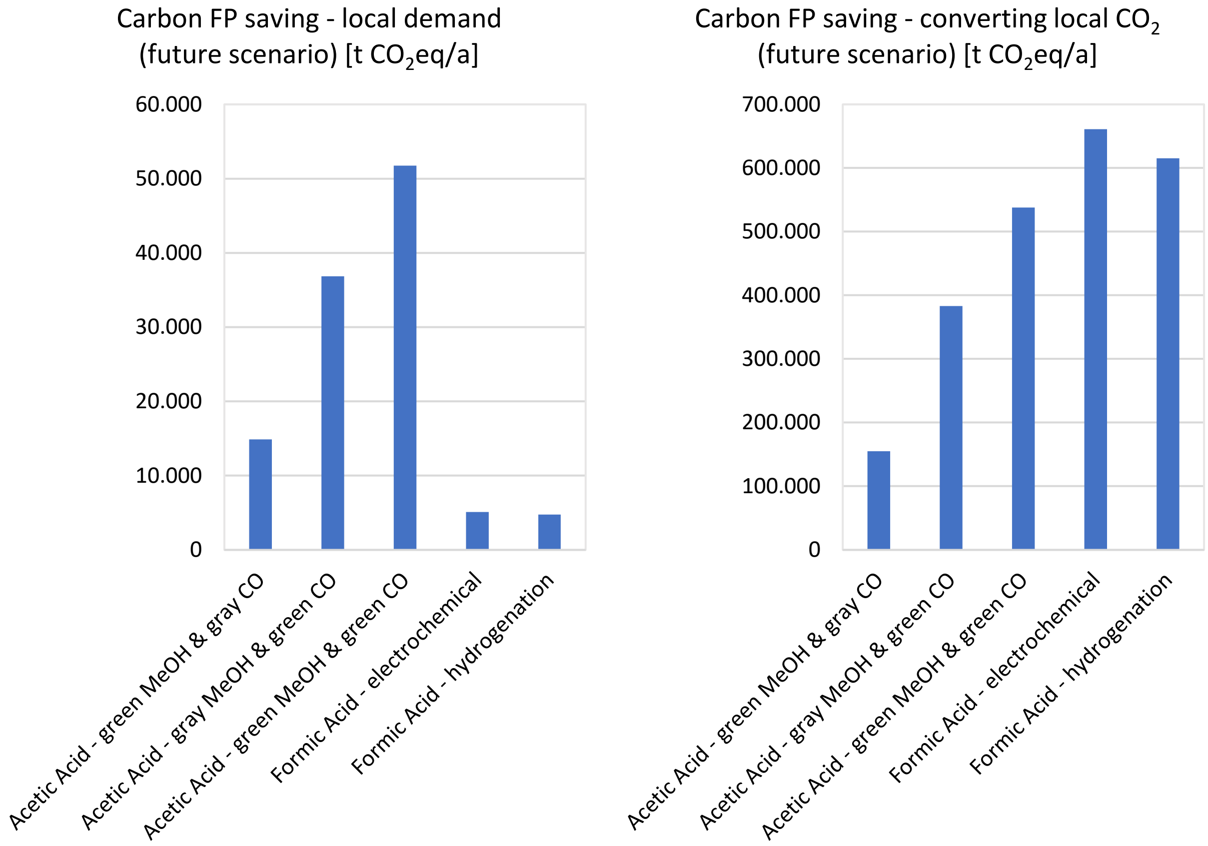


Figure 6-13: Carbon footprint saving of acetic and formic acid production from CO_2, based on future scenario for the Knapsack site. Explanation of wordings: green = CO_2-based, gray = fossil-based.

As a conclusion it can be stated that CO_2-based chemicals can avoid CO_2 emissions compared to conventional processes and can contribute to combat climate change. Some options also bear the potential of having a close to zero or even a negative carbon footprint in the discussed scenarios. But these processes are more costly and financial support by funding or regulatory requirements (e.g., quota for renewable chemicals) measures are required.