The industrial sector in transition - effects of transformation on the local level

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The industrial sector in transition - effects of transformation on the local level

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Decarbonizing the industrial sector of the European Union will bring major changes to the final energy consumption of industry and to the mix of energy carriers used to provide this energy. In the process of decarbonization, some industrial clusters may arise as new major consumption centers of certain energy carriers such as electricity, while demand for other energy carriers may fall away or shift to other clusters or even other sectors. Preparing for these changes requires consideration of many aspects, including an understanding of the different decarbonization technologies available to each branch of industry, their effects on the final energy consumption of single processes and entire branches, and knowledge of where these effects will have relevant impacts upon local infrastructure.

Analyses of industrial energy consumption performed at the FfE have been carried out both from top-down and bottom-up perspectives, and for areas ranging in size from the entire EU to individual NUTS-3 districts, depending on the scope and goals of each project. Regardless of perspective and geographic scope, these analyses are built upon a fundamental understanding of the most energy intensive branches of industry.

In this discussion paper and the accompanying regional profiles, the FfE will demonstrate the potential effects of transforming three key industrial processes upon the regional energy consumption of their respective branches of industry. Data and modeling results obtained in past FfE projects, and currently being expanded and refined in the project TransHyDE-Sys, are drawn upon for this work. These analyses present a glimpse of the insights into both the industrial transformation and its consequences gathered over the course of many projects, as well as the methods and data that enable analyses of industrial consumption at different geographic scales.

In the TransHyDe project, the focus of the FfE's analyses is transformation from the stakeholder perspective, which is why the focus of this research is on the practical transformation of the selected industry clusters. This stakeholder perspective is defined in the project as follows:

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English translation	Original German version
The stakeholder perspective in the context of the transformation of the energy system is characterized by different goals, motivations and resources of the involved and affected persons and institutions. The stakeholders make decisions that further their own interests on the basis of the limited information available to them, with the aim of achieving an individual economic optimum under the given framework conditions.*	*Die Akteursperspektive im Kontext der Transformation des Energiesystems ist geprägt durch unterschiedliche Ziele, Motivationen und Ressourcen der beteiligten und betroffenen Personen und Institutionen. Von ihrem Standpunkt aus treffen die Akteur:innen* auf der Basis eingeschränkt verfügbarer Information Entscheidungen im Sinne ihrer Interessen mit dem Ziel, ein individuelles wirtschaftliches Optimum unter den gegebenen Rahmenbedingungen zu erreichen.*
**A stakeholder is a person who has the power to make decisions within the individual's scope of action. This can be both a natural and a legal entity. If the same interests are pursued, an association of several persons can also constitute a stakeholder.*	**Als Akteur:in wird die im individuellen Handlungsspielraum entscheidungsbefugte Person angesehen. Diese kann sowohl eine natürliche als auch eine juristische Person sein. Werden die gleichen Interessen verfolgt, kann ebenso ein Zusammenschluss mehrerer Personen eine:n Akteur:in darstellen.*

Cooperation with the research institutes of the industry associations involved in the TransHyDE-Sys project will ensure the concerns of industry stakeholders are reflected in the project, while also enabling expansion and further improvements to the data underpinning analyses such as those presented here. Together with the consideration of the transformation from a systemic perspective in further work packages led by our project partner Fraunhofer IEE, TransHyDE-Sys aims to offer a holistic view of the infrastructure requirements the transformation of the energy system and industrial sector will bring about.

Methods

The data used for the analyses of national and regional consumption in this paper is taken from the FfE industry sector model SmInd EU. The national and regional consumption values used in these analyses stem from modeling within a current project, the results of which are still forthcoming. A brief description of the model's methodology is provided here, and more detail is available in /FFE-04 21/, /FFE-179 20/ and /FFE-52 19/.

SmInd EU calculates the national final consumption at a yearly timescale for the EU27+3[2], differentiated by energy carrier and application (e.g., lighting, process heat), in addition to industry branch and production process. The resulting application balances break consumption of each energy carrier down into consumption per application for 12 applications among 13 branches of industry. Bottom-up modeling of selected energy- and emissions-intensive industrial processes is performed based on national production tonnage and specific consumption and calibrated to ensure consistency with the national top-down consumption from the Eurostat energy balances. In a second step, the calculated consumption data is

[2] The 27 EU member states, plus the UK, Norway, and Switzerland.

regionalized from the national (NUTS-0) to the regional level (NUTS-3)[3] using locational data of emissions- and energy-intensive industrial sites from the EU-ETS and E-PRTR registers, as well as Eurostat data on employment and population. Finally, the temporal resolution is increased using normalized load profiles to provide time series of consumption at the hourly resolution. /FFE-179 20/

In addition to the top-down regionalized consumption data drawn from SmInd EU, the analyses featured in this paper include bottom-up calculations of the final energy consumption and emissions for selected processes at industrial sites in three exemplary regions. For these calculations, regions with high levels of final energy consumption were selected from the SmInd EU results, and the consumption per branch of industry examined. Three regions were then selected, each of which features final energy consumption heavily concentrated in a single branch of industry. Using the underlying locational data, the industrial sites of the most relevant branch within each region were then identified, after which additional research was carried out to identify production levels per site.

As a result of multiple dissertations and masters' theses, as well as cooperation with industry partners in many projects, specific consumption values per energy carrier are available for more than 50 industrial processes at the FfE. With production levels of each site identified, the energy consumption of the selected processes in the status quo was calculated by multiplying the production tonnage of each site with the appropriate specific consumption values. In turn, the calculated final energy consumption per energy carrier was multiplied with emissions factors to obtain the status-quo emissions of the selected processes in their industry cluster.

The goal of these analyses is to provide examples of how the transformation of industry can affect local consumption patterns within an industry cluster. For the selection of the transformation technologies to be examined, interviews were held with the affiliated research institutes of the industrial branches, which are also partners in the project TransHyDE-Sys. These provided expert insight concerning the transformation pathways being weighed by the respective branches of industry. An exemplary transformation technology was then selected for each of the three branches based upon the information obtained from these interviews, from internal FfE experts, and from research into measures planned at the industrial sites in question.

Under the assumption of constant production levels, the final energy consumption and resulting emissions for each process and region were then recalculated using the specific consumption of the chosen transformation technologies. Comparing the final energy consumption and resulting scope 1 emissions of the status-quo and post-transformation provides a quantification of the effects of this transformation in the NUTS-3 region of each industry cluster.

In the course of the project TransHyDE-Sys, cooperation with industry partners and the associated research institutions of individual industrial branches will enable the underlying data basis of SmInd EU to be updated and expanded, with additional new regionalized consumption data to be modeled over the course of the project. The database of industrial sites maintained at the FfE will also benefit from these close contacts with further updates, expansion, and validation. In combination, the work within TransHyDE-Sys will not only

[3] The NUTS (Nomenclature of territorial units for statistics) classification is a hierarchical system in which the economic territory of the EU27+3 is split. The NUTS-0 level represents the country level, the NUTS-3 smaller units such as districts (*Landkreise*) in Germany.

provide key insights into the coming hydrogen economy, but also strengthen the analyses of industrial consumption offered by the FfE from both top-down and bottom-up perspectives.

Branch Analyses

Three energy- and emissions-intensive branches of industry are examined here: The iron & steel industry, the chemical & petrochemical industry, and the non-metallic minerals industry. As can be seen in Fehler! Verweisquelle konnte nicht gefunden werden., originally featured in /FFE-179 20/, in 2017 these three branches of industry accounted for nearly two-thirds of the industrial emissions in both the EU27 + 3 and Germany.

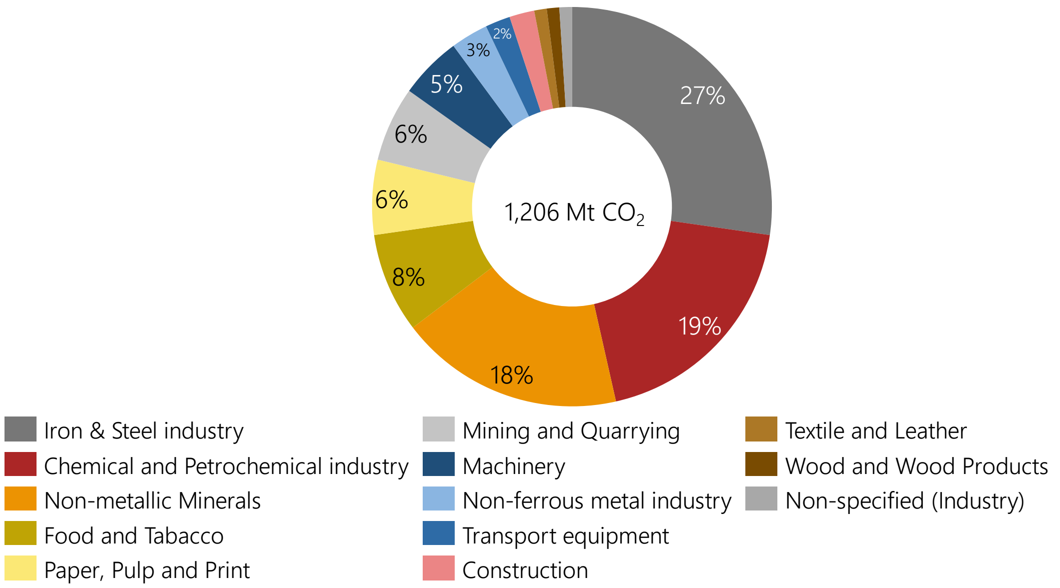

Figure 1: European energy and process related CO_2 emissions (Scopes 1-3) by industry branch in 2017 in Mt CO_2, balanced by the polluter pays principle. Originally presented in /FFE-179 20/, data from Eurostat energy balances /ECE-02 19/ and emissions factors per country from national inventory reports, e.g., /UBA-09 19/. Process emissions from /EUROSTAT-07 20/.

The transformation of these three industries would represent a significant contribution to meeting national and international emissions reduction targets. The role of each of these branches as providers of key inputs for downstream industries also ensures their continued importance to the economy as a whole. Taken together, the decarbonization of these three branches of industry represents a key step towards a more sustainable society, and makes them the focus of these analyses. Each branch will now be examined in turn.

Steel industry

The steelmaking industry is a classic example of energy-intensive industry, with energy consumption of the European iron and steel sector reaching 787 TWh in 2018 /FfE-168 20/. The industry features a high dependency on coal and derived products compared to other industries, with over 70 % of the European iron & steel industry's final energy consumption provided by coal products in 2018, resulting in more than 200 million tons of CO_2 emissions /FFE-168 20/. Germany is a driving force of the European steel industry, representing approximately 25 % of European steel production for each of the past four years /WVS-01 19/, /ESTA-01 20/, /EUROFE-01 21/, /ESTA-01 22/. The importance of the steel sector to many other industries as a provider of input materials combines with the scale of the sector's emissions to make a transformation of the steel sector a foundation of the larger industrial transformation in Germany and beyond. Current methods of steel production will be described in the following section, followed by transformation technologies.

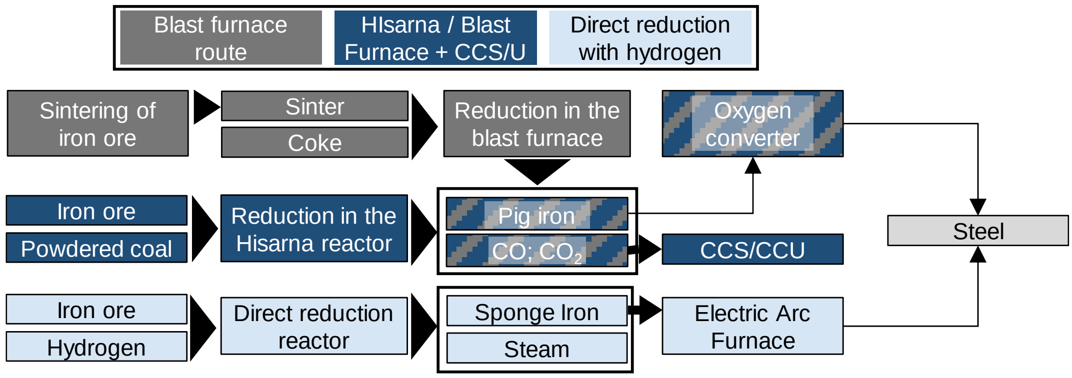

Figure 2: Simplified depiction of process routes for steel production

Steel Production: Status-Quo

The blast furnace route (70 % of production) and the electric arc furnace (30 % of production) are together responsible for the overwhelming majority of crude steel production in Germany today /WVS-01 19/. The blast furnace route begins with the sintering of fine-grained iron ore[4], most frequently at the same location as the blast furnace itself. The ore and additional additives are heated on a moving band until larger clumps of iron ore are formed as the raw materials begin to melt. The larger size of the sintered ore helps ensure the flow of gases through the mass of materials in the column of the blast furnace. To produce crude steel, oxygen must first be removed from iron ore. To do so, a mixture of sintered iron ore and coke is added to the top portion of the blast furnace, while hot air is fed into the bottom portion of the furnace at ca. 1,300 °C. The carbon present in the coke is gasified at these temperatures, leaving the coke and reacting with the oxygen to form carbon monoxide (CO). This reduction gas in turn reacts with the oxygen contained in the iron ore, removing it from the ore and forming carbon dioxide (CO_2). Temperatures in the furnace continue to increase during this process, reaching up to 2,200 °C and melting the reduced iron ore, now referred to as pig

[4] Iron ore can also be processed into pellets for use in the blast furnace. Pelletizing primarily occurs directly at the mine, falling outside of the system boundaries used in this paper. Sintering frequently occurs at the blast furnace site, and will be assumed to be the processing method used here. This enables the inclusion of the energy consumption of sintering in the analysis. /NAV-05 19/

iron. The melted pig iron is collected in the bottom of the furnace before being transferred to the oxygen converter. Here, oxygen is blown into the liquid iron, binding carbon still present in the iron and reducing the carbon content of the pig iron to under 2 %. At this point, the product is no longer as brittle as pig iron, and can now be called steel. /WVS-01 17/ /NAV-05 19/

While steel is produced in the blast furnace using virgin raw materials, the electric arc furnace is primarily used to recycle scrap steel into new crude steel. This difference is the basis for the processes' other designators, the primary and secondary steel production routes. After placing the solid scrap steel in the furnace, natural gas is piped into the furnace to create an atmosphere more conducive to the creation of electric arcs. Along with small amounts of coal, to encourage slag formation, this represents the only direct use of fossil fuels in this process. The electric arcs, powered by electricity in the range of 130 kA, are created between graphite electrodes attached to the underside of the furnace's lid. These arcs can reach temperatures of 3,500 °C in the process, heating the steel scrap to around 1,800 °C and melting it, before the liquid steel is poured off for further handling. /NAV-05 19/

Steel Production: Transformation

Current plans for decarbonization in the steel industry focus on three main options. The simplest of these is a shift of production from the primary (blast furnace) route to the secondary (electric arc furnace) route. The secondary route makes up around 30 % of production in Germany, but is already largely independent of the direct use of fossil fuels /AGORA-07 19/ /WVS-03 21/. If the emissions factor of the underlying electricity mix continues to decrease, the scope 2 emissions of the secondary route will decrease in turn. As only scope 1 emissions are examined in this paper, the emissions of consumed electricity are not considered. Although the secondary route features lower specific emissions, the maximum share of secondary production is limited by the quality, availability, and collection chains of scrap steel /BATAI-01 18/ /OTTO-01 17/.

Primary steel production will therefore remain necessary in moving forward and will thus require a decarbonized process technology to replace the current blast furnace route. Both carbon capture and hydrogen-based direct reduction have been explored as the successor to the blast furnace in recent years, with the hydrogen-based route increasingly the focus of attention. /BATAI-01 18/ /AGORA-07 19/. In the course of expert interviews conducted for this paper, this growing shift towards hydrogen-based direct reduction was seen again in the plans of industry representatives, at the expense of carbon capture technologies /VDEH-02 22/. Hydrogen-based direct reduction will be assumed as the transformation technology here.

Hydrogen-based direct reduction has the same initial goal as the blast furnace route – the reduction of iron ore. Similar to the blast furnace route, the most common direct reduction process variants – MIDREX and HYL-Energion – also take place in a vertical, shaft-like reactor /USTA-02 20/. Pelletized iron ore and lump ore are added to the reactor from above. Hydrogen is used as the reduction agent in place of coke. Heated gaseous hydrogen is blown into the reactor from below and reacting with the oxygen contained within the iron ore as it rises through the raw materials. In place of the carbon dioxide formed in the blast furnace route, in this reaction water vapor is formed. Temperatures remain lower during direct reduction than in the blast furnace route, generally remaining between 800 °C and 1,000 °C. The iron ore is never fully melted, exiting the reactor as solid sponge iron which can be melted in the electric arc furnace. This process is in use today, although both the hydrogen for the reduction reaction and the necessary process heat is provided by natural gas. /AGORA-07 19/ /OTTO-01 17/ /FINK-01 21/ /DOMN-01 18/

Industry Cluster Analysis: Steel

As described above, steel production in the blast furnace is one of the most energy-intensive industrial processes in Europe. The NUTS-3 region selected to demonstrate the effects of the transformation in the steel industry is the German city of Duisburg, which represents a major steel production center both in Germany and in European terms.

Duisburg is not only a key production center of the steel industry, but also represents one of the main German centers of energy consumption across all industries. The region's approximately 61 TWh of yearly industrial final energy consumption represent approximately 8 % of the modeled German industrial final energy consumption for 2019 (723 TWh). Of the 61 TWh the model allocates almost all energy consumption (93 %) to the steel industry, which in turn means that the steel industry

For the analyses concerning effects of transformation measures undertaken in this paper, the focus is placed on the production process of crude steel, from sintering to the oxygen converter. Further downstream steps, such as hot rolling or casting, are not considered. The geographic scope encompasses the following four production locations with blast furnaces in Duisburg contained in Table 1.

Table 1: Production sites with primary steel production via blast furnace in Duisburg and respective production levels /FFE-168 20/, /TKS-02 22/

Location	Company	Production in Mt per year
Duisburg-Huckingen	HKM	4.6
Duisburg-Beeckerwerth	Thyssen-Krupp	5.5
Duisburg	Arcelor Mittal	1.1
Duisburg-Bruckhausen	Thyssen-Krupp	5.5

For the theoretical industrial transformation considered in this paper, the transformation of primary steel production is achieved solely via the replacement of the blast furnace route with hydrogen-based direct reduction, with subsequent melting of the sponge iron in the electric arc furnace. As described above, this reflects the trends seen in the decarbonization plans of German steelmakers discussed in the expert interview.

Based upon the production levels of the considered locations from Table 1, the before-and-after comparison of the energy consumption and emissions of the two production routes using the described methods is depicted in Figure 3:

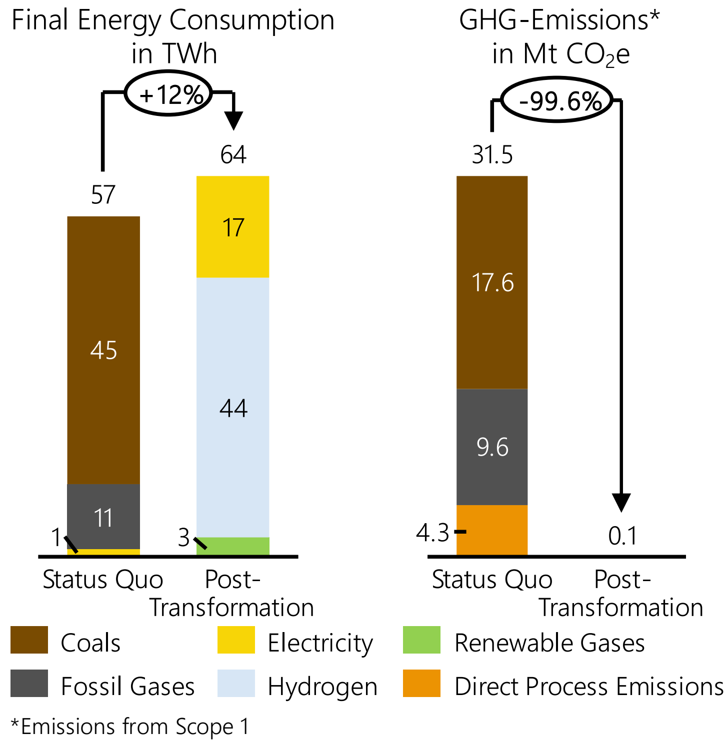

Figure 3: Final energy consumption and scope 1 emissions of the sites considered of the steel industry

The process route shift brings a notable change in the energy carrier split for steel production with it. In addition to the complete substitution of coals and fossil gases in the blast furnace by (green) hydrogen and renewable gases, the removal of sintering from the chain of production reduces the amount of energy required. However, the electric arc furnace (EAF) necessary to melt the sponge iron produced in the direct reduction process more than counterbalances these fuel savings with significantly increased electricity consumption (+16 TWh), leading to a higher overall final energy consumption (+12 %). Despite increased final energy consumption, these fuel switches enable a nearly complete abatement of the scope 1 emissions of steel production, assuming the electricity powering the EAF is generated from renewable sources. The energy consumption and resulting emissions of hydrogen production fall outside of the balancing scope considered here. The use of hydrogen in the DRI process produces no carbon emissions on-site, but the method of its production influences the upstream (scope 3) emissions of the DRI process.

A look at the measures planned and already implemented by local companies supports the choice of hydrogen-based direct reduction as the chosen transformation measure in this analysis. Thyssenkrupp has begun testing the use of hydrogen to replace a portion of the coal dust used as a reduction agent in existing blast furnaces as a first step for reducing emissions at their Duisburg-Hamborn site /TKS-01 21/. In the long term, further deep emissions reductions are possible through a production route shift via the replacement of blast furnaces with direct reduction reactors. Thyssenkrupp plans to bring their first such reactor online in 2026, with a yearly production capacity of 2.5 Mt /TKS-01 22/. In first steps, they have replaced a portion of the iron ore fed into the blast furnace with sponge iron, lowering the amount of coking coal required in the blast furnace /IDG-01 21/, /TKS-01 21/. Meanwhile, ArcelorMittal plans to transport sponge iron from their direct reduction reactor in Hamburg for further processing in Duisburg /ARCE-01 22/.

Although direct reduction seems to be gaining acceptance as the main transformation technology, the opportunities offered by carbon capture continue to be explored. Potential use of CO_2-emissions from the steelmaking process as a raw material for the chemical industry, for example in methanol synthesis, are being explored in the project Carbon2Chem. This would transform the emissions from a waste product into a valuable commodity. The industrial cluster of Duisburg, with companies from both the steel- and chemical branches nearby, is an ideal location for these experiments. /THY-01 18/

Both the amount of (renewable) electricity required directly in the DRI-EAF process and the necessary current strength will demand appropriate electric infrastructure, the provision of which represents a potential challenge for industrial firms and infrastructure operators. The use of hydrogen in the DRI process is also faced with infrastructure-related challenges, most notably the construction of a pipeline network (or repurposing of existing pipelines) for its transport to consumers. The increased generation and transport capacity required to provide sufficient renewable electricity to produce the necessary amounts of green hydrogen also cannot be underestimated.

Chemical and Petrochemical Industry

In contrast to the steel industry, which is largely based upon a homogenous initial product (primary steel), the chemical and petrochemical industry features a highly heterogeneous product palette. Despite this heterogeneity, nine products represent approximately two-thirds of the greenhouse gas emissions of the German chemical sector: Methanol, ammonia, urea, ethylene, propylene, chlorine, benzene, toluene, and xylenes /DECH-02 19/. All of these chemicals represent vital products of the basic chemicals industry and serve as the starting point for a multitude of other products in the chemical industry and beyond. In these analyses, ammonia and ethylene were chosen for closer examination.

Ammonia is one of the most-produced basic chemicals worldwide /DECHEMA-01 17/. In Germany, yearly production is approximately three million tons /VCI-01 21/. Modern agriculture is largely dependent upon ammonia-based fertilizers, with the branch consuming around 80 % of global ammonia production /IEA-07 19/. Demand for ammonia is expected to grow for the foreseeable future, in particular driven by potential new applications as a maritime fuel or as a vector for transporting hydrogen /IEA-07 19/. Worldwide, ammonia production was responsible for around 500 million tons of CO_2 emissions in 2018 /TRS-01 20/.

So-called high-value chemicals (HVC) form the starting point of multiple value-chains in the chemical industry /PROG-01 21/. Ethylene and propylene are the main "target products", while further valuable olefines and aromatics are formed as by-products. Ethylene in particular plays a major role in downstream industries, representing the building block for more than 30 % of all petrochemical products /WI-01 17/. Plastics production (polyethylene and polypropylene) is one notable source of demand for HVCs, as well as further chemical products such as styrene and acrylic acid /DECHEMA-01 17/. Ethylene production in Germany was approximately five million tons in 2020, alongside a further 3,5 million tons of propylene produced /VCI-01 21/.

The status-quo production processes and potential transformation technologies depicted in Figure 4 will be described in more detail in the following sections.

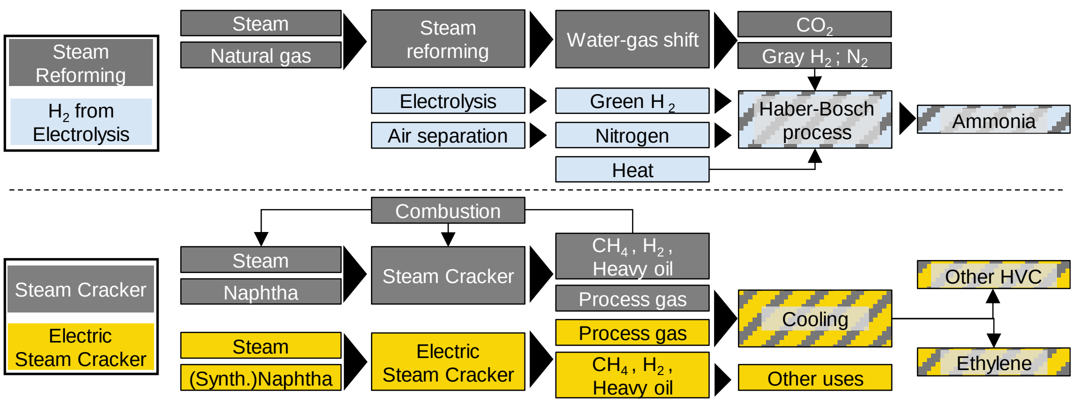

Figure 4: Process routes for ammonia and HVC production

Ammonia Production: Status Quo

The synthesis of ammonia (NH_3) via the Haber-Bosch process is a well-established process in use since the early 20th century. The production chain can be split into two main steps: preparation of process gases and ammonia synthesis. Nitrogen and hydrogen must first be prepared for the final synthesis to ammonia. In today's industrial ammonia production, the required hydrogen is obtained via steam reforming of natural gas. Here, natural gas (methane - CH_4) is reacted with steam (H_2O) at temperatures between 400-500 °C, resulting in a mixture of hydrogen (H_2) and carbon monoxide (CO). A portion of the natural gas is combusted, both to provide process heat and to remove oxygen from the process air in order to obtain the nitrogen required in later steps. Further hydrogen is obtained via the water-gas shift reaction, combining the mixed gases from the steam reforming with additional H_2O molecules, resulting in CO_2 and additional H_2. The two reactants of ammonia synthesis, hydrogen and nitrogen, are then reacted at 450-550 °C under high pressures (150-350 bar) in the presence of iron-based catalysts in the actual synthesis of ammonia. This process is responsible for approximately 2 % of global CO_2 emissions, primarily as a result of producing the needed hydrogen via steam reforming /TRS-01 20/. A transformation of ammonia production will be unavoidable if emissions reduction targets are to be met.

Ammonia Production: Transformation

The main sources of CO_2 emissions in current ammonia production are the combustion of natural gas and the process emissions resulting from the water-gas shift. While the Haber-Bosch process is expected to remain central for future sustainable production of ammonia, the hydrogen and nitrogen it requires can be obtained via routes which forego these emissions /TRS-01 20/. The Power-to-Ammonia route sources hydrogen from the electrolysis of water, splitting H_2O molecules into hydrogen and oxygen using electric energy. The provision of nitrogen requires an additional air separation unit, also powered by electricity. If both of these steps, the provision of process heat, and the compression to 150-350 bar required for the final synthesis are all powered by renewable energy, the process itself will produce no CO_2 emissions.

The technologies required for the Power-to-Ammonia route are individually mature and available, however industrial-scale production will require a major scaling-up of the production units, as well as experience operating them as an aggregate unit at scale to achieve efficient production at similar levels to the current process /DECH-02 19/ /STEV-01 19/. Alternative technologies for ammonia production, such as biological fixation via bacteria (TRL 1), direct electrochemical production (TRL 1-2), or chemical looping processes (TRL 1-4), are being explored, but are all currently at early levels of development /TRS-01 20/. Power-to-Ammonia is the transformation technology applied in these analyses.

Ethylene Production: Status Quo

Current production process to obtain ethylene are petrochemical processes. Naphtha, the main process feedstock used today[5], is produced during the atmospheric distillation of crude oil in refineries, and represents one of many links between the chemical industry and refineries /DECH-02 19/ /SAUIG-01 21/. To obtain the desired HVC, the chemical bonds of the long-chain naphtha molecules must be broken, or "cracked", in a steam cracker to obtain the desired short-chain molecules (ethylene features two carbon atoms per molecule) /REN-02 06/.

To do so, naphtha is first preheated to approximately 650 °C and mixed with heated steam (180-200 °C), with the process heat being provided by recovered waste heat from later process

[5] Although naphtha will be assumed as the feedstock for this discussion paper, liquified petroleum gas can also be used. /DECHEMA-01 17/

steps. This mixture is then fed through the furnace (most often gas-fired) of the steam cracker, reaching temperatures of 750-900 °C in the roughly half-second it remains in the furnace. To prevent further reactions, the process gas is then crash-cooled to temperatures below 650 °C in approximately one-tenth of a second. This serves to prevent the reformation of unwanted larger molecules. The process gas then undergoes a cycle of multiple compression and cooling stages (15-100 °C) before being cryogenically treated and separated into different fractions. Here, the target products, such as ethylene (C_2) and propylene (C_3), are separated and collected, while many by-products are returned for further cracking (propane) or used as fuel for the process (methane). /REN-02 06/

Ethylene Production: Transformation

The potential technological solution for the decarbonization of HVC production considered in this paper is the direct electrification of the steam cracker. In this case, the principle of the unit remains the same, but the fossil-fired furnace of the original steam cracker must be replaced by electrical heating elements capable of achieving the high temperatures required in the process. The energy previously provided by the combustion of byproducts (such as methane) must be sourced from outside of the process, and these byproducts must be disposed of in another manner. The first large-scale demonstration unit is currently under construction in Ludwigshafen, Germany /BASF-02 22/.

Another potential pathway for ethylene production is the Methanol-to-Olefines (MtO) route. A variety of proprietary process exist for the synthesis of olefines from methanol, with the development of these technologies dating back to the 1980’s /JNCE-01 19/. The processes share the common feature of obtaining the target HVC from the input product of methanol via catalytic reactions, but vary in the composition of the output products (e.g., share of ethylene vs. propylene) and the materials used as a catalyst. Methanol is typically first dehydrated to obtain dimethyl-ether, which is then subjected to olefin synthesis reactions in the presence of the chosen catalyst at temperatures ranging from approximately 350-600 °C /UTU-01 08/ /JNCE-01 19/. The resulting target HVC products and byproducts are then cooled and separated in a similar manner to that used in steam cracking /UTU-01 08/.

These processes are largely mature and ready for industrial application, and currently are used in China to synthesize olefines via methanol produced from coal /AGORA-07 19/. Unsurprisingly, this does not offer an advantage over conventional steam cracking in terms of emissions reduction. If this goal is to be achieved, sustainable methanol production via the use of green hydrogen and a sustainable source of CO_2 or via the gasification of biomass will be necessary. Both green hydrogen and biomass are anticipated to be scarce goods in the near future. In addition, the hydrogen-based synthesis of methanol and coupled HVC production via MtO results in a five-fold increase in the energy demand per ton of HVC compared to the cracking of naphtha /DECHEMA-01 17/.

A similar problem faces HVC production from synthetic naphtha. Produced for instance from green hydrogen via the Fischer-Tropsch process, synthetic naphtha could be cracked in conventional or electric steam crackers without significant adjustment to the process. However, the energy consumption for the production of this naphtha is higher still than the MtO process chain, even before the energy still required for the operation of the cracker is considered /DECH-02 19/.

Both of these methods for ethylene production (and other HVCs) offer promising alternatives for decarbonization, if significant amounts of renewable energy are available and affordable.

With conventional naphtha continuing to be produced as a byproduct of locked-in demand for conventional fuels for the foreseeable future, the electrification of the steam cracker represents an achievable first step towards decarbonization and is the technology applied in these analyses.

Industry Cluster Analysis: Chemical Industry

Representing the chemical industry in these analyses is the NUTS-3 region Zeelandic Flanders in the Netherlands.

The Zeelandic Flanders region, similar to Duisburg's status within the European steel industry and within Germany, features not only one of the highest regional final energy consumptions of the chemical industry across Europe, but also represents a highly energy-intensive region within the Netherlands. With an industrial final energy consumption of approximately 30 TWh, the region represents approximately 17 % of the modeled total industrial energy consumption of the Netherlands in 2019 (174 TWh), with around 97 % of this (29 TWh) originating in the chemical industry.

The focus of the following analyses lays on two regional production sites – one producing fertilizers, while the other further processes the ethylene from the on-site steam cracker to produce plastics. In particular, the respective key underlying processes of ammonia (NH_3) production and the production of ethylene in the steam cracker will be examined. In turn, the considered transformation measures are production route shifts to, respectively, Power-to-Ammonia and the use of an electric steam cracker.

Table 2: Production volumes of the chemical industry sites under consideration /PBL-02 19/, /PBL-02 22/

Location	Company	Production* in Mt per year	Year
Sluiskil	Yara Sluiskil B.V.	1.8 (NH_3)	2017
Hoek	DOW Terneuzen	1.8 (Ethylene)	2019

* These production levels represent the production capacities. Given the typically high utilization factors of production facilities, these capacities have been used as the actual production levels.

As described above, a key change in the Power-to-Ammonia route is the provision of hydrogen via electrolysis instead of via steam reforming. Both of these processes are balanced in the energy supply sector, leading to only minor changes in the process balance via the increased electricity required for air separation in the transformed process route. The calculated emissions for both ammonia production and ethylene production include scope 1 emissions. The cumulative final energy consumption and scope 1 emissions of these processes can be seen in Figure 5.

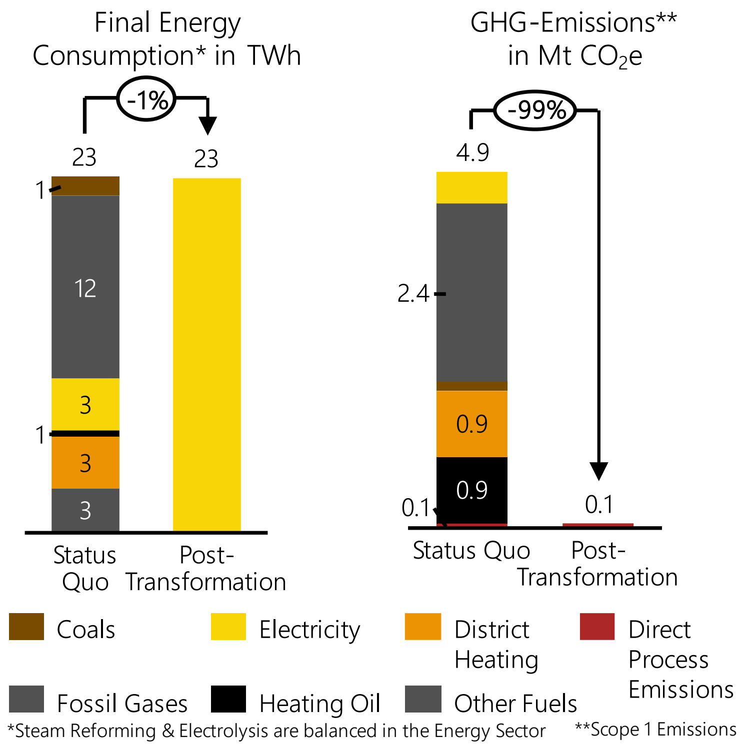

Figure 5: Final energy consumption and both energy-related and process emissions of the chemical industry of the sites considered

Both chemical processes offer an example of the electrification of industrial processes as a means to eliminate the energetic scope 1 emissions, with the Power-to-Ammonia process an example of indirect electrification while the electric steam cracker represents direct electrification. As can be seen in the transition to fully electrified production processes will greatly increase the electrical load of industrial sites. Network operators and industrial consumers will need to increasingly cooperate to ensure the successful electrification of industry is accompanied by any necessary infrastructure improvements.

A look at the region shows that companies in the chemical industry can take advantage of synergies between production sites to reduce their emissions even before an industrial transformation has been fully completed. For instance, Yara Sluiskil added a hydrogen pipeline to their existing ammonia plant. The hydrogen supplied via this pipeline originates as a byproduct of ethylene production in the nearby steam cracker belonging to Dow. This manner of procurement has reduced the direct dependence on fossil fuels in the ammonia plant and provided Yara Sluiskil with a yearly CO_2-savings of approximately 10,000 t, as well as lowering energy consumption by roughly 0.15 PJ per year. /GASUN-01 18/ In the medium run, Dow plans to use byproducts of current processes to produce hydrogen and useful CO_2, as well as transitioning to the use of hydrogen as a fuel source. In the long run, the steam cracker, which is currently powered by fossil fuels, will be electrified. This could occur via retrofitting, or through the complete replacement of the current unit with an electric steam cracker. /DCC-01 21/

A challenge in the electrification of the steam cracker in the past has been the upscaling of electric heating elements to an industrial scale /AGORA-07 19/. A first test unit at industrial scale is currently under construction in Ludwigshafen, Germany /BASF-02 22/. As mentioned above, an electrified steam cracker will require large amounts of renewable electricity and the corresponding infrastructure. While the electrified steam cracker can be powered with renewable electricity, a further challenge for the abatement of emissions associated with ethylene production lies in the nature of the feedstock naphtha. A byproduct of oil refining, the emissions from naphtha production make up a portion of the upstream Scope 3 emissions of ethylene production. These Scope 3 emissions will remain, even if the direct Scope 1 emissions of ethylene production are eliminated. Although Scope 3 emissions are beyond the outside of the boundaries applied in this paper, the climate-neutral production of naphtha or a synthetic replacement is also necessary for a climate-neutral ethylene production. Similarly, the hydrogen required as a feedstock in ammonia synthesis in both the status-quo and power-to-ammonia processes will continue to be a source of upstream emissions as long as it is produced via steam reforming or with electrolysis powered by non-renewable energy. Both the energy consumption and emissions of these upstream process steps are not within the scope of the analyses performed here.

Cement industry

Just as the steel and chemical industries provide the basic building blocks for much of the modern economy, cement and concrete are key ingredients of today's world. In 2019, the German cement industry produced around 24 million tons of clinker and 34 million tons of cement /VDZ-01 19/. In the process, approximately 20 million tons of CO_2 were released due to the combination of chemical changes in the raw material during the clinker production process and energy-related emissions according to the industry's own reporting /VDZ-01 19/. Although trends for the increased use of less carbon-intensive building materials are beginning to emerge, cement will remain a key industrial product for the foreseeable future and methods for lowering emissions of production must be found. The current production process and the potential methods depicted in Figure 6 will be described in the following sections.

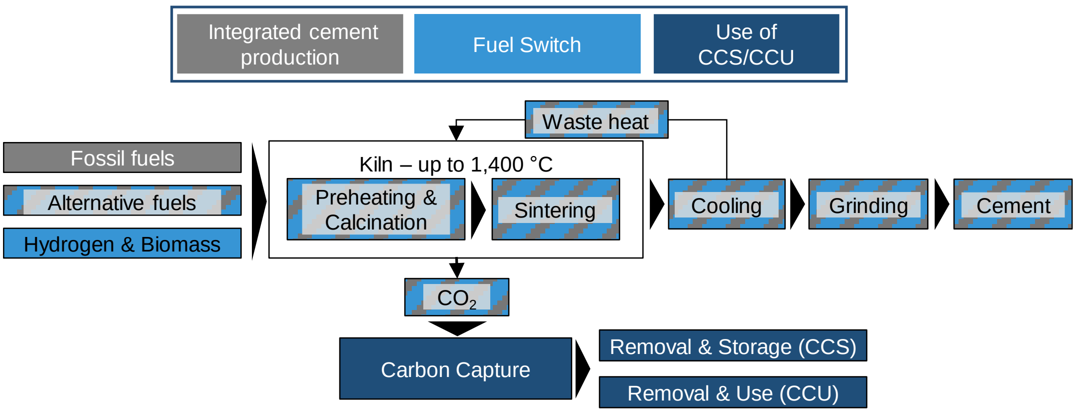

Figure 6: Process routes for cement production

Cement Production: Status Quo

Cement is an agglomeration of gypsum and cement clinker. The production of clinker is both the most energy-intensive and most emissions-intensive aspect of cement production. Clinker production begins with the quarrying, drying, and crushing of stones containing calcium carbonate ($CaCO_3$ – for example, limestone, chalk, or marl) and clay or shale /IEA-02 18/. At integrated production sites, the heat required for the drying step is often provided as recovered waste heat from the rotary kiln. These raw materials are then combined with further materials and ground together until a homogenized mixture is formed, which can be stored or directly processed further. The electrically powered mills used in this process step consume approximately 20 % of the electrical energy used in the production chain. /FFE-123 19/

Transforming this mixture, or raw meal, into cement clinker is a high temperature process, which takes place in a rotary kiln. Before entering the rotary kiln itself, the raw meal is preheated, frequently in a cyclone preheater (also known as a suspension preheater). In this unit, hot gases exiting the kiln or cooling area are blown into a vertically stacked series of preheating chambers from below, while the raw meal is fed in from above. In each preheating chamber, the raw meal is suspended by the gas flowing into the preheating chamber from the opposite direction. Heat is transferred from the gas to the raw meal, which is then separated from the gas stream and fed into the next, hotter, chamber to repeat the process. Upon reaching the bottom of the column, the raw meal has reached temperatures of approximately 900 °C and is then fed into the precalciner. In this combustion chamber, the calcium carbonate undergoes chemical decomposition to calcium oxide at temperatures of approximately 1,000 °C, with gaseous CO_2 also being formed from this chemical reaction. A portion of this process can optionally also be achieved during the preheating step. The calcined meal is then fed into the rotary kiln. /KIT-03 00/ /IEA-02 18/

A rotary kiln is a long, cylindrical tube, up to six meters in diameter and tens of meters long (up to 100 m), positioned at a slight slant from kiln entrance downwards towards the kiln exit /VDZ-02 08/. Fuel is fired directly into the kiln from the bottom, while the rotation causes the raw materials to slide slowly towards the flame, moving through increasingly hotter zones in the process. The meal is heated in this way to temperatures up to 1,450 °C for 30 to 45 minutes, leading to partial melting and chemical changes to the meal, including the completion of the calcination process. After this step, the calcined and partially melted meal has combined into so-called clinker. After cooling, the clinker can be stored or directly ground with electric mills to produce different grades of cement. /KIT-03 00/ /IEA-02 18/

While the clinker production makes good use of waste heat within the process (e.g., using kiln gases to preheat materials), the process is very fuel intensive, requiring approximately 1 MWh of fuel per ton of clinker produced /VDZ-01 19/. In the German cement industry, a significant proportion of this fuel demand (ca. 65 % in 2019) is provided by so-called alternative fuels – largely waste products such as old tires, municipal waste, sewage sludge, or waste wood /FFE-123 19/. The share of alternative fuels as a replacement for more expensive fossil fuels has increased over the past decades and plays a not insignificant role in waste management /VDZ-01 20/. Since many of these alternative fuels consist partially or entirely of biomass, this substitution of fossil fuels also reduces the energy-based emissions of the process. The share of alternative fuels can be further increased according to industry representatives /VDZ-03 22/.

Cement Production: Transformation

In comparison to the other two sectors examined here, the transformation of the cement industry offers a different challenge. The majority of emissions from clinker and cement production result not from the burning of fossil fuels to provide process heat, but from chemical changes in the product /VDZ-01 20/. The direct process emissions, in particular from the calcination step of clinker production make up approximately 60 % of the overall emissions of cement production /FFE-123 19/. While research continues in the cement industry to find alternative binders for future cement products, the required chemical properties of clinker mean that these process emissions will remain for the foreseeable future. Therefore, a deep decarbonization of the cement industry will require both a transition away from fossil fuels and an abatement of these process emissions via carbon capture.

The high flame temperatures required for clinker production (ca. 2,000 °C) make the direct electrification of the rotary kiln very challenging, and would require further technological development to realize /VDZ-01 20/. A transition away from fossil fuels will therefore mean a switch to other fuels. Further increasing the use of alternative fuels, as described above, offers a lower-carbon source of fuel and represents a priority of the industry /VDZ-01 20/. The ability of a cement plant to make dual use of waste incineration, in the form of thermal energy and as a useful raw material, offers an advantage over traditional waste incineration /VDZ-01 20/ /VDZ-03 22/.

The use of hydrogen as a fuel offers another potential alternative to fossil fuels, although hurdles to implementation remain. Higher shares of hydrogen within the fuel mix alter the characteristics of the flame within the kiln /VDZ-01 20/. To ensure adequate heat transfer to the raw materials, the share of hydrogen must be kept below a critical threshold, with levels up to approximately 10 % currently seen as technically achievable /VDZ-01 20/. Given the ability of the cement industry to effectively make use of waste products as fuels and the competing sources of demand for green hydrogen during the upscaling period, the use of larger shares of hydrogen above this 10 % admixture is not expected in the short- to medium-term /VDZ-03 22/.

In these analyses, all three of these tools will be applied as transformation measures. A complete fuel-switch will be applied, with 90 % of fuel demand being met by alternative fuels and 10 % met by hydrogen. The use of post-combustion carbon capture will also be applied.

Industry Cluster Analysis: Cement Production

The exemplary cluster chosen to demonstrate a potential transformation in this paper is the NUTS-3 region of Barcelona, a major city in the north-east of Spain.

The Barcelona region is a center of Spanish industry, representing approximately 11 % (24 TWh) of the modeled final energy consumption in 2019 in Spain (228 TWh). The consumption within the region is spread over more branches of industry than seen in Duisburg and Zeelandic Flanders, but the non-metallic minerals branch (which includes cement production) holds the largest share of consumption with 32 % (7.7 TWh). In the European context the eastern coast of Spain is, together with the northern region of the country and some nordic regions, one of the most important regions of the cement industry. The analyses here consider the five integrated cement works (production of both clinker and cement) in the region, as displayed in Table 3.

Table 3: Cement works in the Barcelona region. Production capacities from /SCAO-01 22/

Location	Company	Production* in Mt per year	
		Clinker	Cement
Vallcarca	Cementos Portland Valderrivas	1.1	1.2
Montcada i Reixac	Lafarge Holcim España	0.8	0.9
Sant Vicenç dels horts	Cementos Molins Industrial	1.5	1.8
Santa Margarida I els Monjos	Cementos Portland Valderrivas	1.8	2.0
Sant Feliu de Llobregat	Cementos Molins Industrial	1.1	0.9

* These production levels represent the production capacities. Given the typically high utilization factors of production facilities, these capacities have been used as the actual production levels.

For these five cement works, the effects of a fuel switch will be examined. As described in the previous section, fossil fuels will be completely replaced, primarily by alternative fuels (90 %), with hydrogen also meeting 10 % of the fuel demand. Additionally, to account for the direct process emissions resulting from the calcination of the raw materials, the effects of carbon capture will be included as an additional transformation technology. It is assumed 95 % of resulting emissions can be abated via carbon capture /PROG-01 21/. The effects of these measures on the final energy consumption and scope 1 emissions of the region can be seen in Figure 7. The use of biomass here represents the share of bio-based waste (such as treated sewage) found within alternative fuels.

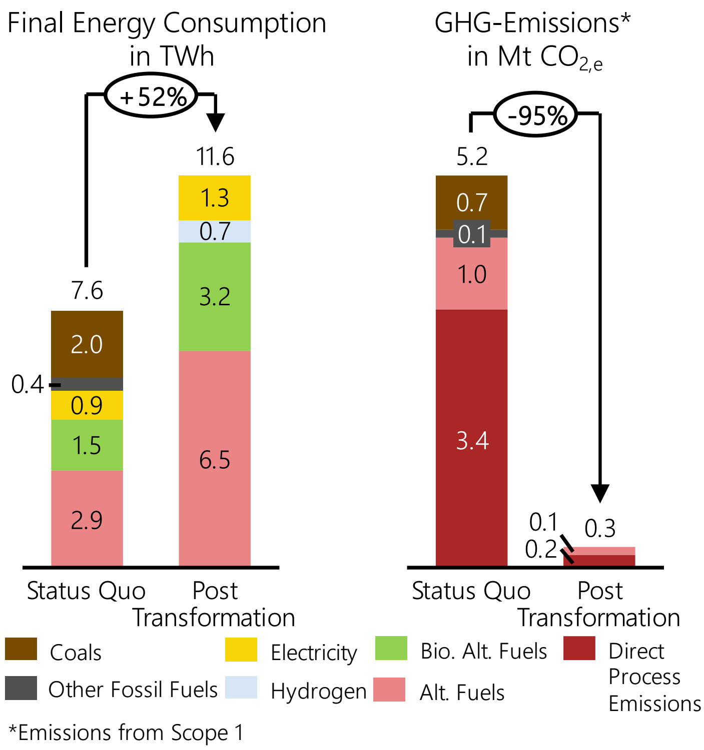

Figure 7: Final energy consumption and both energy-related and process emissions of the cement production sites considered (scope 1 emissions, 2017 electricity mix).

The prospective transformation examined here leads to a notable increase in final energy consumption due to the added energy demand (approximately 0.7 MWh/$t_{Clinker}$) from carbon capture units. However, the energetic scope 1 emissions can be captured along with the direct process emissions. The share of bio-based waste (represented here as biomass) within the overall consumption of alternative fuels was held constant at approximately 33 %. In combination with carbon capture and storage, the CO_2 drawn from the atmosphere during the growth phase of the biomass can be removed from the carbon cycle instead of being re-released into the atmosphere, creating a negative emissions balance /IEA-06 21/. While no concrete decarbonization plans including carbon capture could be identified for the five cement plants considered here, an example can be found in the Bavarian municipality of Rohrdorf, where a carbon capture unit went into operation in September 2022. This pilot project aims to reduce the emissions of the local cement plant and provide the captured CO_2 as feedstock for the chemical industry. /SPZ-01 22/

Conclusion

Within the framework of this discussion paper, three European industrial clusters were analyzed to determine the extent to which a resident industry, particularly its final energy consumption and GHG emissions, is subject to change within the course of the transformation to climate neutrality.

For the resident industry most dominant in each industry cluster, the most energy-intensive processes in the status quo, as well as potential transformation technologies for each process, were first described qualitatively. Subsequently, the final energy consumption and emissions were quantified based upon current production levels at the relevant locations within the industry cluster. The energy consumption values and the resulting emissions for each energy carrier were then re-calculated to represent an imagined application of the chosen transformation technology as part of the transformation to a climate-neutral industry.

In order to drastically reduce emissions, all three of the resident industries considered here are facing changes in the production processes of their goods. This is reflected in some of the examined cases in the form of an increased final energy consumption, while all cases saw a shift of the energy carriers that make up their final energy consumption.

Simplifications were made in the scope of the analysis performed in this paper, which result in some limitations regarding the applicability of the results. Three relevant limitations are described below.

The calculated consumption data is regionalized from the national (NUTS-0) to the regional level (NUTS-3) using locational data of emissions- and energy-intensive industrial sites from the EU-ETS and E-PRTR registers, as well as Eurostat data on employment and population. A potential weakness of this method lies in the use of these databases, as they contain only the largest or most energy- and emissions intensive industries and individual locations. This in turn leads to an over-concentration of industrial consumption in regions featuring such industrial sites, and an underestimation in other regions. The cooperation with European and national organizations representing industrial branches in TransHyDE aims to help correct this weakness by increasing the number of industrial sites considered and both offering primary data concerning energetic consumption as well as validation of model results.

Constant production levels are assumed in calculating the final energy consumption and resulting emissions for each process and region were then recalculated using the specific consumption of the chosen transformation technologies. Comparing the final energy consumption and resulting scope 1 emissions of the status-quo and post-transformation provides a quantification of the effects of this transformation in the NUTS-3 region of each industry cluster. While this type of ceteris paribus analysis neglects many of the complexities involved in the real-world transformation of industry, the results offer examples of the potential changes to industrial consumption that must be accounted for if this transformation is to succeed.

For each process and industry, the effects of a single transformation technology were applied to each location within the industry cluster. In practice, it is conceivable and probable that individual locations or companies will make differing decisions regarding the choice of transformation technology. Each of these choices will also be accompanied by other measures (e.g., increasing the efficiency of processes) not included in the analyses performed here.

Overall, a significant defossilization of the investigated industry clusters seems possible with existing transformation options or those near to maturity. By comparing the considered transformation options with the industry associations involved in TransHyDE-Sys and their transformation strategies, the considered paths appear to be practically valid as well.

This need for the expansion or new construction of industrial plants, in particular taking into account a changed and/or increased final energy consumption, will be subject to a closer examination in the further course of the TransHyDE-Sys project focusing on Germany in the European context. The following questions, among others, will be addressed in the process:

- What is the systemically most favorable infrastructure for H_2 and CO_2? What are the specific costs?
- Where does it make most sense to position electrolyzers and methanation plants?
- How much investment is needed in new and rebuilt hydrogen and CO_2 pipelines, and where?
- How are electricity infrastructure needs evolving?
- How do the different procurement options (e.g., generation in Europe vs. import) and storage technologies for hydrogen affect the power plant fleet?

Declaration

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References

AGORA-07 19 Joas, Fabian et al.: Klimaneutrale Industrie - Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement. Berlin, Wuppertal: Agora Energiewende, 2019.

BASF-02 22 BASF, SABIC and Linde start construction of the world's first demonstration plant for large-scale electrically heated steam cracker furnaces. In https://www.basf.com/global/en/media/news-releases/2022/09/p-22-326.html. (Abruf am 2022-09-09); Ludwigshafen: BASF SE, 2022.

BATAI-01 18 Bataille, Christ et al.: A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. In: Journal of Cleaner Production 2018 (187) 960-973. Amsterdam: Elsevier Ltd., 2018. DOI: 10.1016/j.jclepro.2018.03.107

DECH-02 19 Roadmap Chemie 2050 - Auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland. München, Frankfurt: Dechema, 2019.

DECHEMA-01 17 Bazzanella, Alexis et al.: Low carbon energy and feedstock for the European chemical industry. Frankfurt am Main: DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., 2017.

DOMN-01 18 Domnick, Caroline: Vergleichende Untersuchung und Bewertung verschiedener wasserstoffbasierter Direktreduktionsverfahren zur Senkung der Treibhausgasemissonen in der Stahlproduktion. Bachelorarbeit. Herausgegeben durch Hochschule für Angewandte Wissenschaften Hamburg: Hamburg, 2018.

FFE-04 21 Weiß, Andreas et al.: Simulative Analyse der zukünftigen Netzbelastung - Interaktion von PV und Elektromobilität im urbanen Verteilnetz. In: Tagung Zukünftige Stromnetze 2021. Berlin: Conexio, 2021.

FFE-123 19 Hübner, Tobias et al.: Energiewende in der Industrie - Branchensteckbrief der Zement- und Kalkindustrie. München: Forschungsgesellschaft für Energiewirtschaft (FfE), 2019.

FFE-168 20 Hübner, Tobias et al.: European Steel with Hydrogen - FfE Discussion Paper 2020-04. München: Forschungsgesellschaft für Energiewirtschaft mbH, 2020.

FFE-179 20 Fiedler, Claudia et al.: Modelling transformation pathways for EU27+3 final energy demand using temporally and spatially resolved sector models. In: Conference Proceedings Current and Future Challenges to Energy Security; 5th AIEE Energy Symposium, virtual conference, December 2020. München: Forschungsstelle für Energiewirtschaft e.V., 2020.

FFE-52 19 Guminski, Andrej et al.: Electrification decarbonization efficiency in Europe - a case study for the industry sector. Munich, Germany: Forschungsgesellschaft für Energiewirtschaft mbH, 2019.

FINK-01 21 Fink, Vera: Technische Grenzen des Einsatzes von Strom und Wasserstoff in der Industrie - Technical Limits of the Usage of

Electricity and Hydrogen in the Industry. Masterarbeit. Herausgegeben durch die Technische Universität München - Lehrstuhl für Energiewirtschaft und Anwendungstechnik, betreut durch die Forschungsgesellschaft für Energiewirtschaft mbH: München, 2021.

IEA-02 18 Technology Roadmap Low-Carbon Transition in the Cement Industry. Paris, Geneva: International Energy Agency (IEA), 2018.

IEA-06 21 Unlocking the potential of bioenergy with carbon capture and utilisation or storage (BECCUS). In https://www.iea.org/articles/unlocking-the-potential-of-bioenergy-with-carbon-capture-and-utilisation-or-storage-beccus. (Abruf am 2022-09-10); Paris: International Energy Agency, 2021.

IEA-07 19 The Future of Hydrogen - Seizing today's opportunities. Paris: International Energy Agency, 2019.

JNCE-01 19 Gogate, Makarand R.: Methanol-to-olefins process technology: current status and future prospects. Jawajarlal Nehru College of Engineering, Aurangbad, India: Department of Chemical Engineering, 2019. DOI: 10.1080/10916466.2018.1555589.

KIT-03 00 Achternbosch, Matthias et al.: Herstellung von Zementklinker - Verfahrensbeschreibung und Analysen zum Einsatz von Sekundärbrennstoffen. Karlsruhe: Forschungszentrum Karlsruhe GmbH, 2000.

NAV-05 19 Schlemme, Jannik et al.: Branchensteckbrief der Eisen und Stahlherstellung. Berlin: Navigant Energy Germany GmbH, 2019.

OTTO-01 17 Otto, Alexander; Robinius, Martin; Grube, Thomas; Schiebahn, Sebastian; Praktiknjo, Aaron; Stolten, Detlef: Power-to-Steel - Reducing CO2 through the Integration of Renewable Energy and Hydrogen into the German Steel Industry in: Energies (4), 2017, S. 451. Basel: MDPI, 2017. DOI: 10.3390/en10040451

PBL-02 19 Batool, Masooma, Wetzels, Wouter: Decarbonisation options for the Dutch fertiliser industry. The Hague: PBL Netherlands Environmental Assessment Agency, 2019.

PBL-02 21 Negri, Aurelio, Ligthart, Tom: Decarbonisation options for the Dutch Polyolefins industry. The Hague: PBL Netherlands Environmental Assessment Agency, 2021.

PROG-01 21 Klimaneutrales Deutschland 2045 - Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. Berlin: Prognos AG, 2021.

REN-02 06 Ren, Tao et al.: Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes. In: Energy 31. Utrecht, The Netherlands: Utrecht University, 2006.

SCAO-01 22 Oficemen - Associated Firms. In https://www.oficemen.com/en/associated-firms/. (Abruf am 2022-09-09); Madrid: Spanish Cement Association (Oficemen), 2022.

STEV-01 19 Stevens, Rob: Decarbonized Ammonia for Food and Energy. In: Ammonia Energy Conference 2019; Orlando, Florida: Yara International, 2019.

TKS-01 22 thyssenkrupp beschleunigt grüne Transformation: Bau der größten deutschen Direktreduktionsanlage für CO2-armen Stahl entschieden. Duisburg: thyssenkrupp Steel Europe AG, 2022.

TRS-01 20	Ammonia: Zero-carbon fertiliser, fuel and energy store. London: The Royal Society, 2020.
UTU-01 08	Ren, Tao et al.: Steam cracking and methane to olefins: Energy use, CO2 emissions and production costs. Utrecht: Utrecht University, 2008.
VCI-01 21	Chemiewirtschaft in Zahlen 2021. Frankfurt am Main: Verband der Chemischen Industrie e. V., 2021.
VDZ-01 19	Umweltdaten der deutschen Zementindustrie 2019. Düsseldorf: Verein Deutscher Zementwerke e. V., 2019.
VDZ-02 08	Zement-Taschenbuch - 51. Ausgabe. Düsseldorf: Verein Deutscher Zementwerke e.V. (VDZ), 2008.
WI-01 17	Arnold, Karin et al.: Technologiebericht 4.3 Power-to-liquids/-chemicals innerhalb des Forschungsprojekts TF_Energiewende. Wuppertal: Wuppertal Institut für Klima, Umwelt, Energie gGmbH, 2017.
WVS-01 17	Roheisen- und Rohstahlerzeugung in: http://www.stahl-online.de/index.php/themen/stahltechnologie/stahlerzeugung/ (Abruf: 11.04.2017) Archived by WebCite® at: http://www.webcitation.org/6pdjgN7ip. Düsseldorf: Wirtschaftsvereinigung Stahl, 2017
WVS-03 21	Fakten zur Stahlindustrie in Deutschland 2021. Berlin: Wirtschaftsvereinigung Stahl, 2021.