Deep decarbonisation of the German industry via electricity or gas? A scenario-based comparison of pathways

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Abstract
The industry sector accounts for about 20 % of GHG emissions in Germany. Achieving long-term GHG neutrality also requires industrial emissions to approach zero in the long-term. The German government set an intermediate industry sector target in the range of 49 to 51 % emission reduction by 2030 compared to 1990. While the targets are set, it is yet mostly unclear which technology path industry will and can take towards decarbonisation. Various measures including energy efficiency, biomass, electrification, green hydrogen, power to gas (PtG), circularity, material efficiency, process switch and carbon capture and storage are on the table, but their individual contributions are highly debated.

We present results of a comprehensive bottom-up assessment comparing two alternative scenario pathways to 2050. The first is based on electrification as the main decarbonisation option, while the second builds on the broad availability of green gas. We use the bottom model FORECAST, which contains a high level of technology and process detail. E.g. more than 60 energy-intensive processes/products are included as well as a detailed stock model of steam generation technologies.

Results show that both scenarios reach a GHG reduction of about 93 % in 2050 without using carbon-capture and storage. Remaining emissions are mostly process-related. This requires a fundamental change in industrial energy supply and use, but also in the industrial structure including entire value chains. The electrification scenario experiences an increase of direct use of electricity of about 100 TWh or 50 % by 2050 compared to 2015 plus additional 146 TWh green hydrogen. In the gas focused scenario electricity demand remains stable, while a demand for 337 TWh of green gas emerges by 2050, mainly replacing natural gas use, but also coal in the steel industry and feedstocks in chemical products. Both scenarios assume a substantial improvement in– energy efficiency and material efficiency along the value chain for CO_2-intensive products as well as a strong shift to a circular economy. E.g. the secondary steel route gains market share from about 30 % in 2015 to 60 % in 2050. In the basic materials industries a process switch to low-carbon production routes takes place assuming the market introduction and fast diffusion of low-carbon technologies, which are today only at pilot or demonstration scale. In addition, the electrification scenario also requires a carbon source for the hydrogen-based olefine production. Here, we assess the option to use remaining process-related CO_2 emissions from lime and cement plants.

Such fundamental change in the industrial structure can only happen when the regulatory frame is adapted and addresses the major challenges ahead. Among these are for example the higher running costs of CO_2-neutral processes, the expansion of infrastructure, the effective implementation of CO_2 price signals along the value chains and the reduction of uncertainties regarding large strategic investments in low-carbon processes.

Introduction
Achieving long-term GHG neutrality also requires industrial emissions to approach zero in the long-term. The German government set an intermediate industry sector target in the range of 49 to 51 % emission reduction by 2030 compared to

1990. While the targets are set, it is yet mostly unclear which technology path industry will and can take towards decarbonisation.

We present results of a comprehensive bottom-up assessment comparing two alternative pathways. The first is based on electrification as the main decarbonisation option, while the second builds on the broad availability of green gas. We use the bottom model FORECAST, which contains a high level of technology and process detail. E.g. more than 60 energy-intensive processes/products are included as well as a detailed stock model of steam generation technologies and a representation of other cross-cutting technologies.

Approach used

The FORECAST model is used to calculate the scenarios for the industrial sector. A detailed description of the model is available in Fleiter et al. (2018). FORECAST is a bottom-up energy demand model. It depicts the technology structure of the industry and calculates energy consumption and emissions as well as costs at process level. The input data for the modelling include economic performance per industry, energy and CO_2 prices, assumptions on policy instruments (e.g. investment grants), structural data such as energy and GHG balances, and techno-economic data of the depicted technologies. Statistical data, empirical studies, literature and expert estimates are used for parameterization. For the development of decarbonization scenarios/paths a wide range of different decarbonization strategies can be considered including for example energy efficiency, fuel switch or process switch.

Scenario definition and assumptions

Two scenarios are defined: Focus Electricity and Focus Gas. In the following, the definition of the Focus Electricity scenario is described in more detail and, based on this, the Focus Gas scenario is presented as a variant of the Focus Electricity scenario by changing selected assumptions. The central assumptions described below start with the economic development and then move on to the techno-economic assumptions regarding decarbonisation strategies for each industry sector. For both scenarios, it is aimed for a GHG reduction of 90–95 % by 2050 compared to 1990.

An average annual growth rate in (gross) value added of around 1 % p.a. is assumed for industry. It is assumed that the energy-intensive basic industries will grow somewhat more slowly, while e.g. the mechanical engineering sectors will be the growth drivers. In addition to the development of value added, the physical production volume of the basic industry is an important influencing factor for energy consumption and GHG emissions. A slight decrease in tonne production is assumed for some products, especially for cement and steel. These declining production volumes already include assumptions of increased material efficiency along the value chain and especially in the construction industry. Products such as aluminium, flat glass or chlorine show a rather constant development.

With regard to the assumptions on decarbonisation strategies, the modelling approach ranges from very endogenous modelling to exogenous assumptions. E.g. the stock and market of steam generators or efficiency technologies are endogenously modeled based on the cost competitiveness of alternative solutions. On the other side, the market the market introduction and diffusion of new production routes (e.g. H_2-based steel production), material efficiency improvement rates and process switch to secondary routes are exogenously defined. Table 1 shows an overview of the technology-specific assumptions on the different decarbonisation strategies per sector for the **scenario Focus Electricity**. In principle, the scenario contains an ambitious **efficiency progress** in the area of process and cross-sectional technologies. Best available technology (BAT) is used in all sectors and, in addition, **innovations** are adopted which have at least proven their feasibility on a pilot scale (current Technology Readiness Level 6). In the genera-

Table 1. Overview of major assumptions for the scenario Focus Electricity.

	Energy and process efficiency	Energy carrier and process switch	Recycling and circular economy	Material efficiency and substitution
Iron and steel	BAT, thin slab or strip casting	H_2-DRI, plasma steel	Electric steel share increases from 30 to 60 % (scrap-based secondary route)	Efficient steel use Substitution
Chemicals	BAT, oxygen depolarized cathode, selective membranes	Electric boiler, H_2 for olefines, methanol, ammonia, some biomass for feedstocks	Increased recycling of plastics reduces primary use by 30 %	Reduction and substitution of plastics consumption Reduction of ammonia use in fertilizers
Cement	BAT	Biomass, low-carbon cement types	–	Reduction of cement use, minimum clinker share
Glass	BAT, oxy-fuel, excess heat use	Electric furnace	Increase of flat glass recycling	Material efficient glass use for container glass
Paper	BAT, innovative paper drying, enzymatic pretreatment, black liquor gasification	Electric boiler, biomass, district heating, heat pumps	Paper recycling increases from 77 to 86 %	Material efficient paper use
Others	BAT, innovative cross-cutting technologies	Electric boiler, large scale heat pumps	–	–

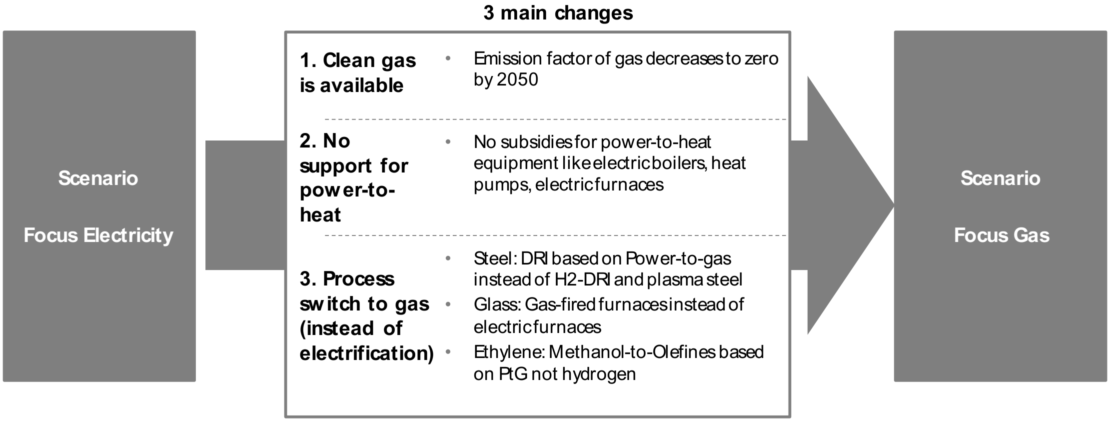

Figure 1. Definition of the scenario Focus Gas as a variant of the scenario Focus Electricity.

tion of process heat, (direct) **electrification** is consistently relied on wherever possible. Where temperature levels permit, large industrial heat pumps are used. Direct electrification is often associated with the replacement of furnaces and boilers. For direct electrification in steel production and certain processes in the chemical industry currently no technology at TRL 6 or higher is available. Here, instead of hydrocarbons **hydrogen** is used, which is produced in the scenario by means of water electrolysis using renewable electricity. Strategies in the direction of a **circular economy** are made at product level. Particularly noteworthy are assumptions on increasing recycling rates for steel and plastics. Progress in **material efficiency** is assumed in all industries and leads to a decreasing production volume compared to a reference scenario. **Carbon capture and storage** (CCS) is not included as a strategy in both scenarios.

The **scenario Focus Gas** is defined as a variant of the scenario Focus Electricity. Instead of focusing on an electrification strategy, it is assumed that CO_2-neutral gas will be available for industry via the gas infrastructure. Consequently, the scenario contains significantly fewer changes on the part of industrial processes. Figure 1 shows the individual levers that distinguish the Focus Gas scenario from the Focus Electricity scenario.

It is assumed that CO_2-free gas will be available. This is included in the model by reducing the emission factor of natural gas to 0 by 2050 (2030: 5 % admixture of green gas, 2040: 25 %, 2050: 100 %). As a result, with the underly CO_2 prices (increase to 200 euros in 2050), gas as an energy source will become more economical again in the long term from a business perspective than CO_2-intensive energy sources. In the Focus Electricity scenario, financial support for power-to-heat plants is necessary in order to push them into the plant stock with significant proportions at an early stage, as the CO_2 price is only high enough to achieve the same effect in later years. This financial support is eliminated in the Focus Gas scenario. The conversion of selected processes to gas is also assumed. For steel, a direct reduction based on PtG is implemented. For glass, gas-fired furnaces will continue to be used instead of switching to electric furnaces. Ethylene production continues to use methanol-to-olefins, but based on synthetic gas instead of hydrogen.

Results

In the following, the scenario results are first described on the basis of the resulting GHG emissions and energy consumption, before individual decarbonisation strategies are discussed and the development at sectoral level is described. Both scenarios are presented in a comparative manner.

OVERVIEW: GREENHOUSE GAS EMISSIONS

In both scenarios, the industrial sector achieves a GHG reduction of about 93 % by 2050 compared to 1990, with remaining GHG emissions coming almost exclusively from processes and some small remaining quantities of fossil fuels, although it is expected that these would be substituted in subsequent years after 2050 if the momentum continues. By 2030, the scenarios achieve a reduction of 56 % (Focus Electricity) and 55 % (Focus Gas). Both scenarios thus slightly exceed the German industry sector target of a 49 % to 51 % reduction by 2030. There are significant differences between the two scenarios in the year 2040, with the Focus Electricity scenario already recording a much lower reduction than the Focus Gas scenario. This is due to the fact that the Focus Electricity scenario is based on a fundamental change in industrial process heat generation, which requires a longer lead time due to long lifetimes and slow circulation rates. In the Focus Gas scenario, on the other hand, the current gas-based processes are largely maintained. The late reduction after 2040 is mainly due to the assumptions regarding the admixture path of CO_2-neutral gas into the natural gas network. Earlier availability of CO_2-neutral gas and higher blending rates would lead to a lower GHG emission reduction already in 2040. In 2050, the picture is again similar in both scenarios. The remaining approximately 18 million tonnes of CO_2-equivalent GHG emissions are dominated by process-related emissions. Although these will decline continuously until 2050 due to process changes, material efficiency and innovative cement types, a significant base remains here. Figure 2 shows the development of total GHG emissions and individual sources.

From the remaining approximately 18 Mt CO_2-equivalent emissions just over 50 % is distributed relatively broadly across several sectors and products, while the other (almost) half (~8 Mt) is concentrated in cement and lime production. Despite the remaining emissions, cement production is undergoing a fundamental change and is significantly reducing its emissions

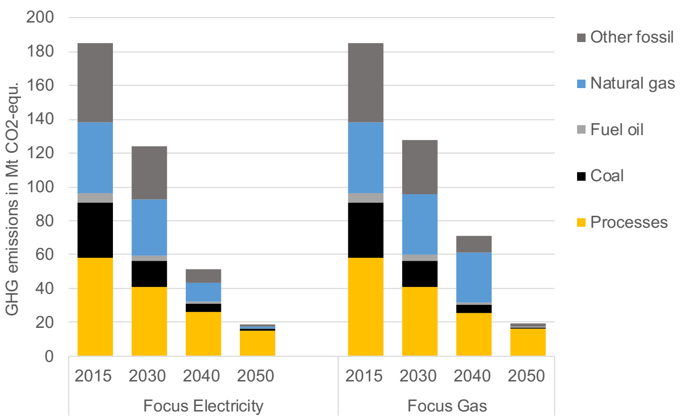

Figure 2. Development of GHG emissions in the scenarios Focus Electricity and Focus Gas by emission source.

compared to 1990. The measures that have been implemented include the more efficient use of concrete and cement in the construction industry, a reduction in the clinker factor and the increased use of clinker substitutes as well as the diffusion of innovative low-CO_2 cement types, a very high use of biomass and the use of the best available technology in terms of energy efficiency. For a further reduction of the remaining emissions in cement and lime production, only carbon capture and storage (CCS) is currently available. However, this is not included in the scenario. A comprehensive use of CCS for the remaining CO_2 emissions from cement and lime production would allow the industry's overall emission reduction to be further increased from 93 % to over 95 %.

OVERVIEW: FINAL ENERGY

Final energy consumption changes fundamentally in both scenarios up to 2050 (see Figure 3). In total across all energy sources, a significant and continuous decline can be observed in both scenarios. Starting at 715 TWh in 2015, final energy consumption drops by 26 % in the scenario Focus Electricity and by 22 % in the scenario Focus Gas by 2050. The sharper decline in the scenario Focus Electricity is due to the greater efficiency of electric processes.

The changes at the level of individual energy sources are much more pronounced in both scenarios. Up to the year 2030 the scenarios develop relatively similarly. Coal consumption in particular falls rapidly and almost halves by 2030 relative to 2015, while natural gas consumption also falls sharply to 45 TWh (Focus Electricity) and 30 TWh/a (Focus Gas) from 218 TWh in 2015. Biomass in particular shows an increase, and roughly doubles by 2030, increasing to about 30 TWh in both scenarios. Hydrogen and synthetic gas do not play a significant role in 2030. Electricity consumption declines somewhat in both scenarios, reaching 218 and 211 TWh in Focus Electricity and Focus Gas, respectively. Thus, the efficiency induced decline is partly offset by an increase in electrification in the scenario Focus Electricity.

By the year 2050, the use of all types of fossil fuels has almost vanished. However, the target picture in 2050, as well as the path to 2050, differ significantly between the two scenarios. In the scenario Focus Electricity, there is a strong increase in the direct use of electricity and hydrogen. Direct electricity use increases by almost 100 TWh – despite ambitious efficiency gains – and clearly dominates final energy consumption in 2050, with a share of 60 % (31 % in 2015). This increase is to a large part due to an extensive electrification of industrial process heat. With the exception of the primary route of crude steel production and cement and lime production, all industrial furnaces are electrified (glass, steel processing, foundries, non-ferrous metals). Process steam is generated by means of electric boilers. Where possible, high-temperature heat pumps are used. Accordingly, the use of ambient heat increases to almost 50 TWh in 2050. Hydrogen appears in the energy mix from 2040 on and reaches a level of 39 TWh by 2050. The demand for hydrogen comes solely from steel production, which is being switched from the current blast furnace route to direct reduction and plasma steel using hydrogen. The increase in the use of biomass to 72 TWh is largely due to its use in cement production, which is well-placed to convert to biomass combustion.

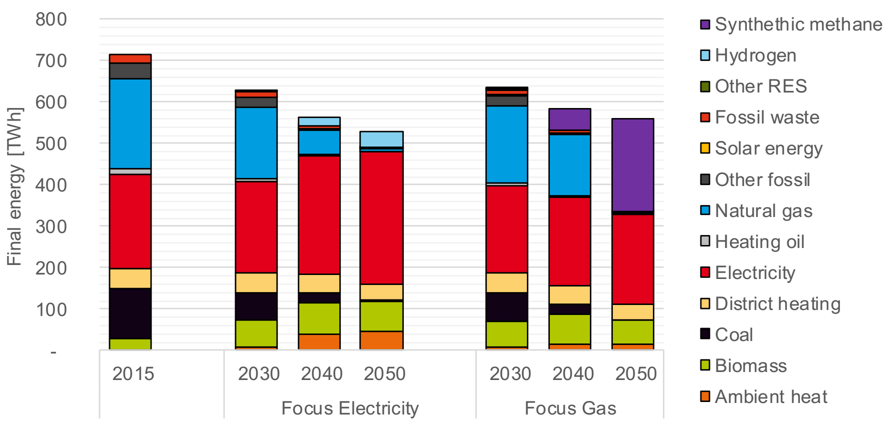

Figure 3. Development of final energy consumption until 2050 in both scenarios.

In the scenario Focus Gas, electricity consumption remains roughly at the current level in 2050. Significant progress in energy efficiency is compensated by a moderate electrification of process heat. The most important feature of this scenario is that especially from 2040 on large quantities of synthetic methane are added to the gas network, which is completely converted by 2050. The demand for synthetic methane is 224 TWh in 2050, which is about the same level as the demand for natural gas in 2015. The production of synthetic methane or hydrogen is outside the system boundaries of the industrial sector, according to the energy balance.

In addition to the energy consumption of fossil fuels, their use as feedstock also plays an important role in the energy and CO_2 balance of the industrial sector and represents a major challenge for the transformation to a CO_2-neutral industry. Figure 4 shows the development of material demand for energy sources for selected processes (ammonia, methanol, ethylene/olefins). For these processes, the current demand is about 150 TWh, of which a good 114 TWh is naphtha for the production of olefins. In both scenarios, the switch to CO_2-neutral feedstocks is accelerating after 2030.

In the Focus Electricity scenario, hydrogen becomes the central feedstock, with a total demand of 107 TWh in 2050, with biogenic raw materials accounting for a much smaller share of around 18 TWh. This result is influenced by the conversion of olefine production from today's steam crackers to the methanol-to-olefins route, which maintains ethylene as the central platform chemical. The hydrogen is used for the CO_2 neutral methanol production, with the necessary carbon could be obtained from remaining CO_2 emissions of the cement and lime plants. In the Focus Gas scenario, almost the entire feedstock base is converted to synthetic methane by 2050. Only ammonia production is converted to (CO_2-free) hydrogen. The demand for synthetic methane thus increases to 95 TWh by 2050. The slight decrease in feedstock consumption in both scenarios is due to a corresponding decrease in the production of ammonia and olefins.

Both scenarios require a very high amount of renewable electricity for direct use but also for the production of green gases. Assuming a conversion efficiency of 70 % for hydrogen and 60 % for synthetic methane, the scenario Focus Electricity represents a total electricity demand of 553 TWh in 2050 (direct use: 319, synthetic methane: 0, hydrogen: 234) and the scenario Focus Gas of 774 TWh (direct use: 217, synthetic methane: 531, hydrogen: 26) including both final energy and feedstocks.

ENERGY EFFICIENCY

Both scenarios assume an ambitious progress in energy efficiency. This includes the use of best available technology (BAT) for process technologies as well as for cross-cutting technologies such as engines, compressed air or steam generation. The progress goes beyond this in many areas by using innovative efficiency technologies that are not yet available on the market today. In combination with measures of material efficiency and recycling, a significant reduction in final energy consumption is thus achieved – despite increasing value added in the industrial sector. The resulting impact can be quantified showing the energy intensity of industrial gross value added, which roughly halves in both scenarios. While for each Euro of value added generated by the industry sector about 1.47 GJ of energy input were necessary in 2015, this value falls to 0.76 (Focus Electricity) and 0.81 (Focus Gas). The difference between the scenarios is explained as the switch to electric processes in some cases also results in higher process efficiency.

Despite this ambitious improvement, energy efficiency can only make a certain contribution to decarbonisation - even if the available potential is largely exploited. In addition, the decarbonization of industry requires a fundamental change in many processes, which is often associated with the replacement of existing plants. In these cases, the (incremental) optimization of efficiency is not necessarily target-oriented in the long term. In both scenarios, the majority of the reduction effort is achieved by switching to CO_2-neutral energy sources.

ENERGY CARRIER SWITCH TO BIOMASS AND ELECTRICITY

Switching to CO_2-neutral or low-CO_2 energy sources for the generation of process heat is a central lever for reducing industrial CO_2 emissions. In the FORECAST model, the use of energy sources is modelled endogenously on the basis of the

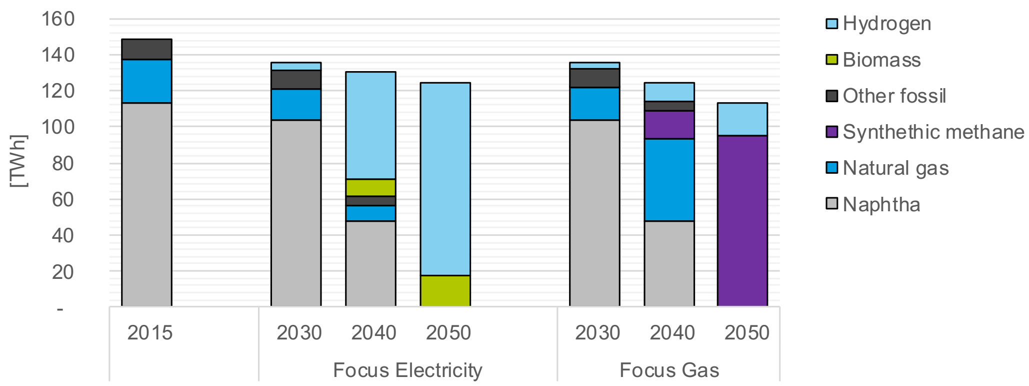

Figure 4. Development of feedstock consumption for the production of ethylene, methanol and ammonia in both scenarios.

economic efficiency of alternative heat supply options. This includes the generation of process steam, but also heat generation by means of industrial furnaces. In basic materials industries temperatures of more than 1,000 °C are often necessary. Here, only biomass and biogas as well as the use of renewables via secondary energy sources such as electricity, hydrogen or synthetic gas come into question. The conversion of process heat generation to biomass or renewable electricity is in many cases associated with fundamental conversions or the replacement of furnaces and steam generators. Besides economic considerations, the change of energy source in many processes depends on technical restrictions. For example, a minimum use of coke or coal is required in the blast furnace for steel production. In these areas, a comprehensive change of energy sources is only feasible if it is accompanied by a fundamental process change. In the FORECAST model, both the economic evaluation and the technical restrictions at process level are simulated and taken into account (Rehfeldt et al. 2018; Rehfeldt et al. 2020).

Figure 5 shows the corresponding results for the evolution of electricity and biomass demand for process heating. In both scenarios, biomass use increases substantially until about 2030 from today's 30 TWh to about 70–80 TWh in 2030. After 2040 it falls again towards 2050. Electricity demand shows very different patterns in the two scenarios. The scenario Focus Electricity experiences a sharp increase from today's about 20 TWh to nearly 140 TWh in 2050. However, most of this increase takes place after 2030. The scenario Focus Gas shows a doubling of electric process heating to about 40 TWh in 2050. Given the decreasing overall final energy demand, the shares of both electricity and biomass are increasing substantially in both scenarios towards 2050.

ENERGY CARRIER AND FEEDSTOCK SWITCH TO SYNTHETIC GAS (PTG)

The use of synthetic gas is only included in the scenario Focus Gas. The purely energetic use of synthetic gas to generate process heat in industrial furnaces and for steam generation is associated with low conversion costs on the demand side, because the equipment for firing natural gas can be further used. Starting from an established technological and economic basis for the use of natural gas in the existing energy system, PtG can maintain and expand in industrial furnaces and process steam generation. In doing so, it replaces (together with direct electricity use, biomass and ambient heat) coal and heating oil, as well as non-renewable waste and other fossil energy sources. The use of natural gas/PtG for process heat generation increases from 176 TWh (100 % natural gas) in 2015 to 216 TWh (100 % PtG) in 2050.

The scenario Focus Gas also assumes a switch of feedstock use from fossil fuels to synthetic gas. For steel production, the availability of PtG means that the methane-based direct reduction process, which is already technologically mature (but which is generally not economically competitive in Germany at present), can be used. In combination with increased use of electric arc furnaces and supported by higher secondary production shares, it completely replaces the coal-based blast furnace route by 2050. The olefins ethylene (C2) and propylene (C3) as well as C4 products, which as platform chemicals form the basis for branched and deep value chains in the chemical industry (e.g. plastics, solvents). They are converted to alternative process routes no longer based on naphtha, but on methanol (C1), from which longer-chain olefins are produced. The production of methanol from methane is of central importance. While in 2015, methanol is used mainly as an admixture in fuels and produced in a quantity of about 1 Mt per year, the methanol demand as a basis for ethylene production increases to about 15 Mt per year by 2050. Further processing into ethylene, propylene and C4 products requires no raw materials other than methanol and comparatively small amounts of additional energy (about 5 TWh of electricity for cross-sectional applications such as engines and pumps).

ENERGY CARRIER AND FEEDSTOCK SWITCH TO HYDROGEN

Most of the resulting hydrogen use in the scenario Focus Electricity is observed for the supply of feedstocks. In the scenario Focus Gas hydrogen is only used as a raw material in the pro-

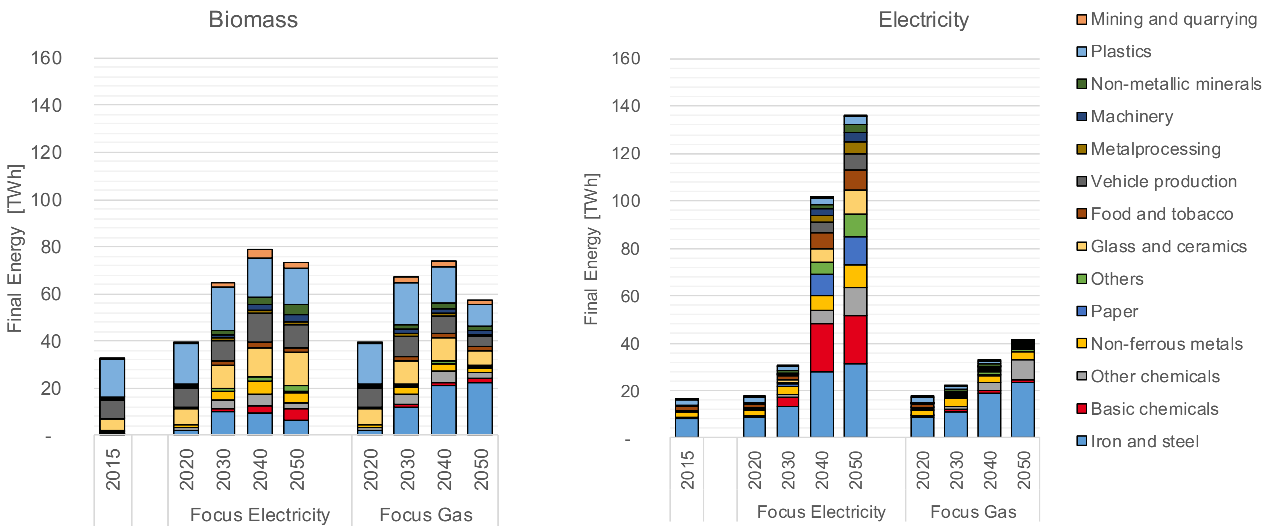

Figure 5. Development of final energy demand for electricity (right) and biomass (left) in both scenarios for process heating only.

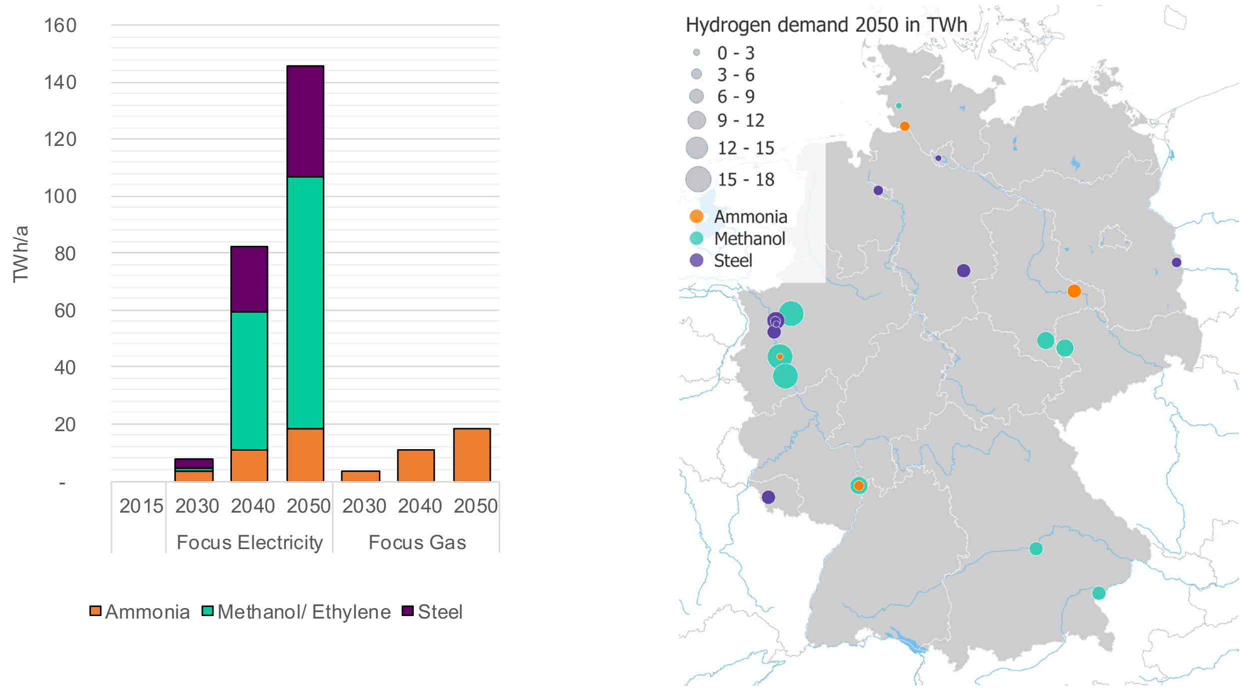

*Figure 6. Comparison of hydrogen demand in both scenarios (left) and geolocalised demand in the scenario Focus Electricity (right) *, **.*

* *Assumption: PtG as used in the scenario Focus Gas is produced outside the industry-system boundary and not reported as hydrogen.*

** *The figure only shows conceivable locations that have been identified using the following key assumptions: Ammonia sites are retained and scaled according to their share of total capacity in 2015. Blast furnace sites are used as sites for hydrogen-based DRI and hydrogen plasma processes based on their capacity in 2015. The significantly increasing capacities for methanol production are be located at today's steam cracker sites, as the ethylene value chain will remain locally connected.*

duction of ammonia (NH_3), where it is used directly. Prior refinement to methane would be counterproductive for this process, since the carbon would then have to be separated again (as in the current natural gas-based process), e.g. in a steam reforming process.

Hydrogen use in the scenario Focus Electricity is summarized in the following. Steel production is switched to hydrogen-based processes. Specifically, two innovative processes for steel production are considered in the scenario Focus Electricity. First, direct reduction with hydrogen, which is similar to the natural gas-based direct reduction process. Second, direct steel production in a hydrogen plasma process. Both share the production capacities released by the phase out of blast furnace operations by 2050 (approx. 7.4 Mt each). The existing natural gas-based direct reduction (approx. 0.5 Mt in 2015) is additionally converted into hydrogen-based direct reduction. The hydrogen demand for ammonia is identical with the Focus Gas scenario. Ethylene production in the Focus Electricity scenario is divided into two parts. First, the methanol route already used in the Focus Gas scenario, but now based on hydrogen (2.6 Mt). This makes the supply of carbon necessary and offers a starting point for CCU concepts. Energetically, however, only the contribution of hydrogen is relevant. Secondly, an ethanol-based route of ethylene production (1.4 Mt), which uses biomass as raw material as an alternative to hydrogen (18 TWh). Thus, on the raw material side, almost 39 TWh of hydrogen will be needed in the steel sector (energetically and as feedstocks) and 107 TWh as feedstock for methanol and ammonia in 2050, and 18 TWh of biomass for the ethanol route of ethylene (as feedstocks) (Figure 4). Hydrogen thus dominates the raw material supply of the chemical industry in the scenario Focus Electricity by 2050 (see Figure 6). The demand for hydrogen can be localised by taking existing locations of methanol, ethylene, ammonia and steel producers into account (see Figure 6). It can be observed that hydrogen demand will very likely peak in a few large demand hot spots.

PROCESS SWITCH AND INNOVATIVE LOW-CARBON PROCESSES

In both scenarios, the transition to an almost CO_2-neutral industrial production requires fundamental changes in the production of mass products in the basic industries such as ammonia, olefines, steel, glass and cement, which currently use fossil fuels and fossil feedstocks to a large extent. Innovative low-carbon processes, some of which can potentially achieve CO_2 neutrality, are currently being developed (Table 2). These rely on direct or indirect electrification and thus on the actual and economic availability of renewable electricity. Other approaches pursue material substitution strategies, e.g. in the cement industry. Direct electrification includes the electrically heated glass smelter, which is already used on a comparatively small scale for the production of container glass. Indirect electrification includes the use of hydrogen produced by electrolysers as an energy carrier, reducing agent (steel: H_2-DRI, H_2-plasma) and raw material (chemistry: H_2-methanol, H_2-ammonia). Material substitution strategies include the market launch of new types of cement (low-CO_2 cement), which use smaller proportions of the raw material limestone and in some cases require less energy input.

Although all these processes show great potential for emission reduction, there are substantial economic uncertainties that have so far prevented their widespread implementation (beyond pilot and demonstration plants). For this reason, technical questions of feasibility on an industrial scale have not always been answered yet. At the same time, there are currently several projects dedicated to the implementation of these technologies (see assessment of TRL and selection of literature in Table 2). In this study it is therefore assumed that the market introduction on an industrial scale is possible between 2025 and 2030. A complete reorganisation of production routes is then necessary by 2050 in order to bring the scenarios examined to a 93 % GHG emission reduction relative to 1990. For the sake of simplicity, the market diffusion is assumed to follow a linear growth.

CO_2 CAPTURE AND USE (CCU)

In the scenario Focus Electricity, the steam crackers in olefine production are replaced by the methanol-to-olefines route. In addition to green hydrogen, CO_2 is required to produce the methanol. Apart from air separation, possible sources of CO_2 are processes whose decarbonization is not possible or only possible with difficulty due to process-related emissions. These include above all emissions from cement and lime kilns. According to the current status, it is expected that the costs of a CO_2-free methanol route will be lower if it uses captured CO_2 from industrial processes than if air capture technology is used. However, this picture may change in the future in case of a dynamic cost degression of air separation technologies (Fasihi et al. 2019; Keith et al. 2018).

A simple CO_2 balance for the year 2050 shows that the entire remaining CO_2 emissions from cement and lime plants would not be sufficient to supply the demand required by methanol production. The CO_2 demand for methanol production sums up to 17.7 Mt CO_2 in 2050, while all cement and lime plants under operation in 2050 emit about 12 Mt. In this scenario, about 5.7 Mt CO_2 would need to come from other sources like waste incineration or direct air capture. While there is high uncertainty in these results (production output, energy mix, process innovations) this already indicates that CO_2 (or more precisely climate neutral carbon) becomes a scarce resource.

To judge on the potential for implementation of a CCU network and provide the basis for more precise cost calcula-

Table 2. Overview of innovative low-carbon processes included.

Sector	Low-carbon technology (LCT)	Reference technology	TRL of LCT	GHG reduction compared to ref. technology [%]	Diffusion (Focus Gas if different)		Sources
					2030	2050	
Steel	H_2-DRI + EAF	Blast furnace route	7	Up to ~95 %[1] (remaining fossil fuel use in the EAF)	4 % (0 %)	21 % (0 %)	(Vogl et al. 2018; Fischedick et al. 2014; ASTIER et al. 1982; Arens and Vogl 2019)
Steel	Plasma Steel	Blast furnace route	3–4	Up to 100 %[1]	0.5 % (0 %)	20 % (0 %)	(Hiebler and Plaul 2004)
Cement	Low-carbon cement (-30 %, high Belite share)	Portland Cement (Alite-based)	8–9	25–30 %	3.6 %	12.3 %	(Chan et al. 2019)
Cement	Low-carbon cement (-50 %, Calcium-Silicate-Hydrate)	Portland Cement (Alite-based)	7	50 %	3.6 %	12.3 %	(Chan et al. 2019)
Cement	Low-carbon cement (-70 %, recarbonating)	Portland Cement (precast concrete)	8–9	30–70 %	7.2 %	24.5 %	(Chan et al. 2019)
Glass	All-electric melting	Natural gas (Regenerative burner)	6–7	Up to 100 %[1]	20 % (0 %)	100 % (0 %)	(Rehfeldt et al. 2020)
Chemicals	Electrolysis-H_2 as feedstock for ammonia	Feedstock: Natural gas (Steam reforming)	7	Up to 100 %[1]	20 %	100 %	(Bazzanella and Ausfelder 2017)
Chemicals	H_2-Methanol (with CCU)	Natural gas steam reforming	7	Up to 100 %[1, 2]	15 %	100 %	(Bazzanella and Ausfelder 2017)
Chemicals	Ethanol from biomass	Ethanol from biomass	9	–	–	–	(Bazzanella and Ausfelder 2017)
Chemicals	MtO (C2-C4-synthesis from methanol)	Steamcracking (Naphtha)	8–9	<0 to > 100 %[1, 2]	0 % (0 %)	65 % (100 %)	(Bazzanella and Ausfelder 2017)
Chemicals	Bio-Ethylene (from ethanol)	Steamcracking (Naphtha)	8–9	Up to 100 %	0 % (0 %)	35 % (0 %)	

[1] *Assumption: hydrogen and electricity demand is produced based on renewable energies.*

[2] *Depending on the origin and use of the CO_2 bound in the product. In this study, the required CO_2 is covered by CCU from process-related emissions from lime and clinker production and released into the atmosphere (these emissions are balanced in the non-metallic minerals sector).*

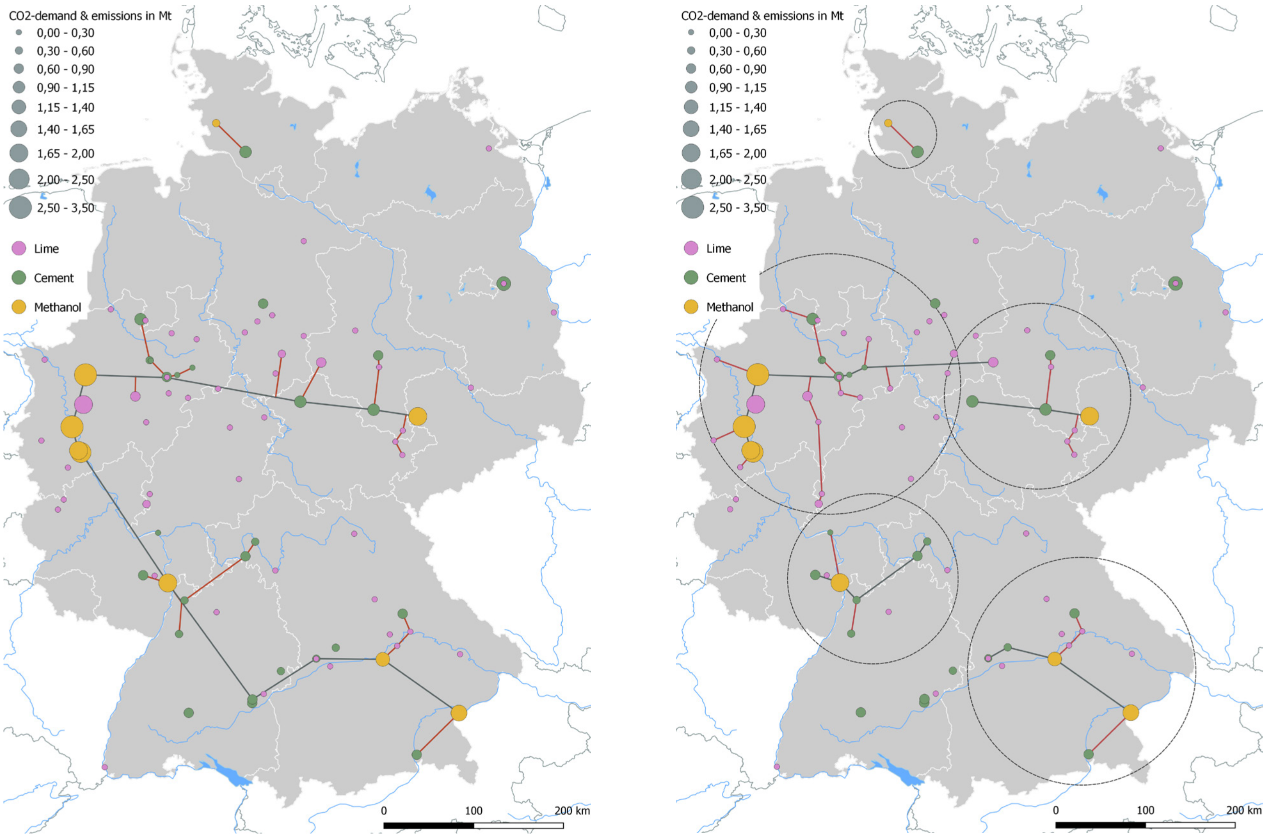

Figure 7. Possible CO_2 infrastructure to connect CO_2 sources (cement and lime plants) with CO_2 sinks (methanol plants) in the scenario Focus Electricity in 2050.

tions, in the following a simple approach is used to estimate the infrastructure needs. Here, the infrastructure to transport the CO_2 from the respective locations of the sources (cement and lime) to the locations of the sinks (chemicals/refineries) is estimated. Two possible solutions were identified by means of a site analysis. Taking into account distance, potentially available CO_2 quantities (based on emissions) and reasonable transport logistics, Figure 7 shows the two possible variants for a CO_2 pipeline network: As integrated solution (left) and cluster solution (right). The figure shows all locations in Germany where cement plants, lime plants/kilns and refineries/chemical plants are currently located (year 2020). This allocation to individual sites should not be seen as a projection or actual expected development. The aim of this analysis is therefore not to make statements about individual locations, but merely to depict the regional character of a necessary CO_2 infrastructure.

CIRCULAR ECONOMY

The expansion of material recycling not only helps to save primary raw materials, but in most cases also leads to a significant reduction in energy consumption in production. For steel, aluminium, paper, glass and plastics, the energy consumption of the secondary routes is sometimes many times lower than the consumption of the primary route (e.g. primary aluminium ~60 GJ/t versus secondary aluminium ~10 GJ/t; crude steel from primary (blast furnace) route ~ 18 GJ/t versus crude steel from electric arc furnace ~3 GJ/t; paper from virgin fibres ~13 GJ versus paper from recovered fibres ~9 GJ). Correspondingly, the further expansion of the circular economy shows great potential for decarbonisation of industry. In the FORECAST model, the primary and secondary routes of selected CO_2-intensive products are mapped separately, allowing the recycling rates to be included in the scenarios in detail via exogenous shifts in production volumes. Technical and economic obstacles, such as the availability of recycling material or deviating product qualities of the secondary route are included in the exogenous assumptions.

While the secondary routes have already been expanded significantly in the past for many materials, especially for paper, aluminium and glass, and the remaining potential of these materials is rather low, the secondary route for steel and plastics grows significantly compared to today in both scenarios. In particular, the increase in the share of **secondary steel** from around 30 % in 2015 to 60 % in 2050 will result in high CO_2 reductions, as the primary route via coal and coke input in the blast furnace is very CO_2-intensive. For **plastics** recycling we assume an increase of 15 percentage points for **glass** particularly an increase in flat glass recycling is assumed. **Paper** recycling increases from 77 % today to about 86 % in 2050. Secondary **aluminium** increases to 58 % from 54 % today. The above assumptions on recycling rates are similar in both scenarios. It shall be noted that strictly following the scenario assumptions with a 100 % low-carbon/CO_2-neutral processes in 2050 also for the primary routes, the shift to secondary routes might not save additional CO_2 emissions. However, it reduces energy consumptions and system costs substantially and by that makes the scenarios more efficient and better achievable.

MATERIAL EFFICIENCY

The efficient use of CO_2-intensive materials along the value chains has a high untapped potential for reducing CO_2 emissions and energy consumption (Allwood et al. 2011). CO_2-intensive materials are often available in large quantities and their costs play only a minor role in the investment decision for the respective end products (e.g. steel costs as a proportion of the price of a car). Measures to increase material efficiency can be very diverse and can, for example, minimize waste in the production process, minimize the use of concrete and steel in building construction due to more precise structural calculations or reduce the thickness of packaging material such as glass bottles. In the FORECAST model, material efficiency progress is defined as an exogenous change in the production quantities of more than 50 CO_2-intensive products depending on the scenario.

The same material efficiency assumptions are made for both scenarios. For the products crude steel, paper, cement and container glass, a material efficiency progress of 10 % is assumed. This means that the production quantity of the products in both scenarios is 10 % lower in 2050 than would be the case in a theoretical reference development without material efficiency gains in the same year. Further scenario-related trends are taken into account for selected products. For example, the demand for lime is declining more sharply as its use in blast furnaces and flue gas desulphurization in coal-fired power plants is no longer required in 2050. The production of ammonia is also falling more sharply, as the use of artificial fertilizers in agriculture has been assumed to be declining.

How ambitious are these assumptions on material efficiency? Compared to the literature, the available potentials for material efficiency improvement are certainly higher for all products than what is assumed in the scenarios (Allwood et al. 2012). Accordingly, the assumptions can be considered moderate to cautious. On the other hand, the realisation of the potential requires a fundamental change in the regulatory framework. Material costs currently play a low role in economic decisions. As many CO_2-intensive products are used in the construction industry, this is the key sector for implementing an effective and successful material efficiency strategy.

Conclusions

Both scenarios achieve a 93 % reduction in greenhouse gas emissions from the industrial sector by 2050 compared with 1990 – even without the use of Carbon capture and storage (CCS). This requires a fundamental change in industrial energy supply and use, but also in the production structure including important value chains. In detail, the following (selected) strategies are critical prerequisites to achieve the transition as outlined in the presented scenarios.

- Low-CO_2 processes are available on TRL 5–7. The coming decade must see their "scale-up" to industrial scale. The processes enter the market from 2025/2030 on and achieve 100 % stock diffusion by 2050 in the basic industries.
- Green electricity or green gas is available in sufficient quantity and electrification or synthetic gas are displacing fossil fuels.
- Green hydrogen supplies the chemicals and steel industries. (Infrastructure needs to be in place.)
- Biomass can be used in many industries within the limits of its sustainable potential and reduces costs and the demand for CO_2-neutral electricity and gas.
- Energy efficiency will be further ambitiously increased and existing potential exploited using best available technologies.
- The circular economy continues to gain ground: Electric steel is used for quality steels, expansion of plastics recycling and building materials recycling gain momentum.
- Material efficiency increases along the value chain, especially in the construction industry.

In order to initiate these technical developments and to implement them as far as possible by 2050, the regulatory framework needs to be changed radically, going beyond the policy instruments currently implemented and decided upon. Central challenges are, for example, the higher running costs of CO_2-neutral processes, the expansion of infrastructure, the effective implementation of CO_2 price signals along the value chains and the reduction of uncertainties regarding large strategic investments in low-carbon processes.

A reduction of emissions beyond 93 % would have to address the remaining emission sources in industrial processes. Here, especially the production of cement and lime still generates residual emissions and thus offers additional reduction potentials. CCS could be a possible option to achieve further reductions. However, it should be borne in mind that in the scenario Focus Electricity the carbon of these residual emissions is used as a raw material for the production of CO_2-neutral methanol. Here, another carbon source would therefore have to be used.

In both scenarios, the investment needs are expected to increase due to the conversion of the industrial plant stock. In particular, however, the running costs will increase, as the conversion to more expensive energy sources will be extensive and CO_2 costs will be internalized. In the scenario Focus Electricity, the assumed electrification requires a stronger conversion of process heat generation and the construction of new industrial furnaces. In the scenario Focus Gas, production can in many cases be continued with today's mostly natural gas-fired plants. In this scenario, however, the running costs increase more strongly, since synthetic gas as an energy source will be more expensive than renewable electricity.

A comprehensive assessment of the related energy system costs in both scenarios is an important next step for further research. Such an assessment should include the investment and running costs of all decarbonisation strategies as well as the connections with the rest of the energy system, e.g. via the supply costs of renewable electricity and gas.

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