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A Brief Analysis of the Decarbonisation Pathways of German Industry and Their Application to China

Sino-German Energy Transition Project

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German Energy Agency

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The report "A Brief Analysis of the Decarbonisation Pathways of German Industry and Their Application to China" presents future technology options for decarbonising the steel, chemical, cement, pulp & paper and aluminium sectors, as well as cross-sectoral technologies. Furthermore, the report highlights different policy instruments to decarbonise industry. The report is published by GIZ in the framework of the Sino-German Energy Transition Project. The project supports the exchange between Chinese government think tanks and German research institutions to strengthen the Sino-German scientific exchange on the energy transition and share German energy transition experiences with a Chinese audience. The project aims to promote a low-carbon-oriented energy policy and help to build a more effective, low-carbon energy system in China through international cooperation, policy research and modelling for mutual benefit. The project is supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) in the framework of the Sino-German Energy Partnership, the central platform for energy policy dialogue between Germany and China on a national level. From the Chinese side, the National Energy Administration (NEA) supports the overall steering. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH leads the project implementation in cooperation with the German Energy Agency (dena) and Agora Energiewende.

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Contents

1. Executive Summary

1. Germany has set ambitious climate protection targets, requiring a break from "business as usual".

After twenty years of stagnating industrial emissions, Germany has set a legal obligation to reduce industrial emissions by one-third by 2030. By 2045, the goal of net greenhouse gas (GHG) neutrality must be achieved.

2. To achieve these climate protection targets, far-reaching and rapid changes are necessary in German industry.

In the future, the main energy source for German industry will be electricity, either directly or indirectly (materially via hydrogen derivatives). In the cement industry, as well as in parts for the provision of high-temperature heat (> 500°C), direct electrification is not possible, which is why greenhouse gas-neutral fuels are used. Furthermore, in the steel and chemical industries, the material use of fossil fuels must be replaced by hydrogen and sustainable carbon sources. Implementation depends on new technologies.

3. In German and Chinese industry, the transformation of the steel, chemical and cement industries relies on new technologies to achieve the complete reduction of process- and energy-related emissions.

In the steel industry, greenhouse gas-neutral primary steel production depends on replacing coal as a reducing agent. Using hydrogen as a reducing agent in a new plant design would reduce most process-related emissions. Furthermore, a new process design makes it possible to use electricity from renewable energy sources in electric arc furnaces. Together, these measures will lead to the decarbonisation of the primary steel production process. The use of CO_2 capture technologies is necessary to neutralise process emissions in the cement industry. In the chemical industry, the use of carbon as a material feedstock currently relies primarily on natural gas, oil and, in China, coal. To achieve net-zero GHG emissions, carbon demand must be replaced by sustainable carbon sources (biomass, CO_2 from Direct Air Capture (DAC), carbon-rich waste). New carbon sources require other technologies, such as pyrolysis/gasification, methanol-to-olefins/aromatics and Fischer-Tropsch synthesis.

4. The electrification of the process heat supply is an essential cross-sectoral technology for decarbonising industry.

The decarbonisation of process heat is necessary in every sector. The most efficient option is to use heat pumps and electrode boilers for the temperature range of 100–500°C. These technologies enable direct electrification and, if demand-side management (DSM) measures are implemented, offer the advantage of responding to electricity production in the grid, thereby reducing costs and emissions.

Deployment must be linked to the development of renewable energy and the power grid and requires the coordination of a wide range of stakeholders.

5. Transformation is only possible through a combination of regulatory and market-based measures, in which the CO_2 price can play a key role as the main instrument.

Decarbonising industry requires the introduction of new technologies in the most important sectors, which are associated with high investment costs and, in some cases, also high operational costs. The CO_2 price plays a key role in promoting sustainable technologies by pushing conventional technologies out of the market. With German industry facing a reinvestment cycle and simultaneously having to stay within German climate protection targets, additional instruments are necessary to make "green" production methods competitive with conventional technologies to enable investments. In particular, green lead markets and carbon contracts for difference (CCfDs) can achieve this.

In addition to market-based instruments, incentives should be put in place in areas such as waste heat utilisation, the circular economy and the use of efficient technologies in order to reduce the energy demand of the industrial sector. In particular, regulatory requirements for the use of technologies or even bans on certain product groups are recommended in combination with incentives, e.g. for particularly efficient technologies or quotas for the use of certain "green" or secondary materials.

2. Introduction

The German energy transition aims to shift the entire energy system away from fossil and nuclear fuels and towards climate-neutral energy carriers within one generation. Achieving these ambitious goals in the industrial sector – which accounts for more than 20% of German CO_2 emissions – requires a fundamental transformation. In the short term, significant contributions to the decarbonisation[1] of the sector are only possible through energy efficiency gains. In the long term, process conversions and a shift to renewable energy will have a significant impact on reducing CO_2 emissions through widespread application.

2.1. Climate targets

The guiding principles and benchmarks of Germany's climate protection policy are the agreements of the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations, 1992) and its related Protocols of Kyoto (1997) (United Nations, 1998) and Paris (2015) (UNFCCC, 2015). For the Kyoto Protocol, the European Union (EU) committed itself to reducing its greenhouse gas (GHG) emissions by 20% by 2020 compared to 1990. In the subsequent Paris Agreement, the signatory states agreed to take the necessary steps to limit the increase in global average temperature to well below 2°C above pre-industrial levels, as well as to make efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

The 2019 EU Green Deal set ambitious climate targets to stipulate rapid emission cuts: it aims for a 55% reduction in net emissions by 2030 compared to 1990 and overall climate neutrality[2] in 2050 (European Commission, 2019).

In 2019, the German government passed the *Bundes-Klimaschutzgesetz* (Federal Climate Protection Act), setting the first legally binding climate protection targets. The aim of this act is to ensure that the national climate protection target is achieved. Therefore, the Climate Protection Act and other energy policies are based on three key pillars: security of supply, economic efficiency and climate protection. Specifically, it aims to phase out nuclear power, coal and eventually all fossil fuels by improving energy efficiency, increasing the use of renewable energy and coupling sectors.

The amended Federal Climate Protection Act of 2021 sets emissions reductions in line with the ambitious EU targets. It mandates a 65% reduction in gross emissions by 2030 compared to 1990 and climate neutrality by 2045. Moreover, it sets binding Scope 1 GHG reduction targets for the years 2020 and 2030 in the building, transport, industry and agriculture sectors, as well as the land-use, land-use change and forestry (LULUCF) sector, as permissible emission levels. Year-specific targets have been set for all sectors except the energy sector. If the targets are not met, measures are prescribed.

Scope 1 emissions refer to direct GHG emissions from sources owned or controlled by an organisation (for example, emissions associated with fuel combustion in furnaces or vehicles or production emissions from owned or controlled process equipment). Scope 2 represents indirect GHG emissions by generating the electricity purchased and consumed by an organisation. The emissions occur at the facility where electricity is generated (World Resource Institute, 2004)[3].

[1] Definition of decarbonisation: Reducing the use of carbon-based energy sources to zero (dena, 2021).

[2] Definition of climate neutrality: "Concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal as well as accounting for regional or local biogeophysical effects of human activities that, for example, affect surface albedo or local climate" (IPCC, 2018).

[3] The Greenhouse Gas Protocol (GHG Protocol) is a private transnational set of standards for carbon accounting and reporting for businesses and, increasingly, the public sector. The standards of the GHG Protocol are mostly linked to those of the international climate policy regime and close regulatory gaps that have not yet been addressed by governments. It is considered the most widespread standard for the preparation of greenhouse gas balances.

2.2. German industry – energy consumption and emissions

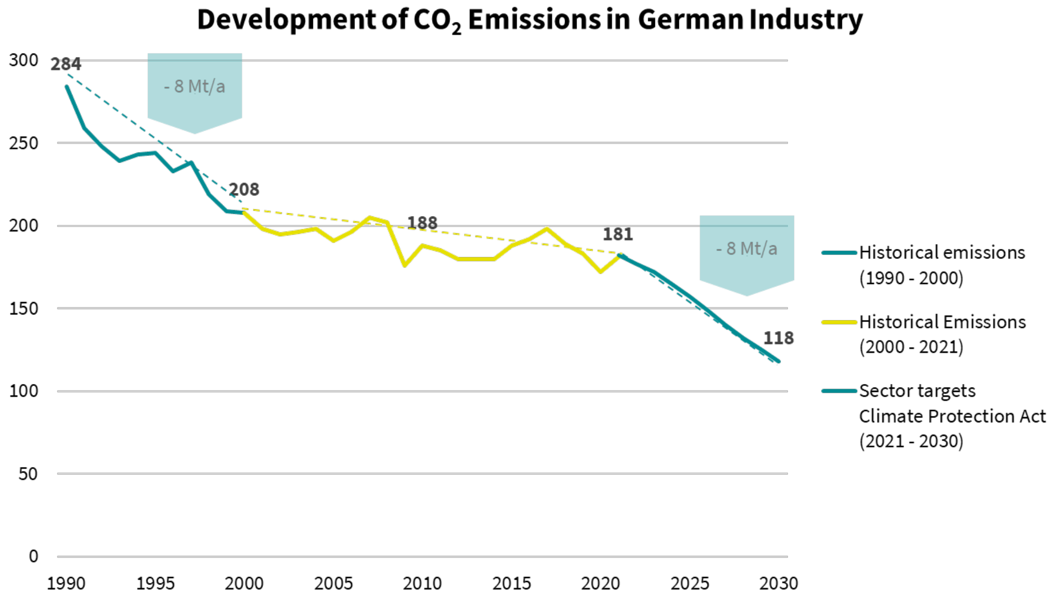


Figure 1 Historical emissions in the industrial sector and sectoral targets until 2030 (UBA, 2022b)

In 2018, the industrial sector consumed 722 TWh, which corresponds to about 38% of Germany's final energy demand. Due to increased efficiency and new processes, the energy demand for industry is projected to fall to around 638 TWh by 2030 and to less than 580 TWh by 2045 (dena, 2021). Due to the conversion of one-third of steel production to reduction and the extensive phasing out of coal in other sectors, coal consumption will be approximately halved by 2030 (dena, 2021).

In 2018, the industrial sector emitted more than 189 Mt of CO_2 equivalent (Statistisches Bundesamt, 2022a). shows the shares of the individual subsectors in the total emissions of the industrial sector and their absolute emissions, as well as reduction pathways until 2045. With around 30%, the iron and steel industry accounts for the largest share of emissions, followed by the chemical industry (19%), cement clinker production (17%), paper (3%), and glass and ceramics (3%). The remaining emissions from industry amount to 49 Mt of CO_2 equivalent (25%). The GHGs covered here include carbon dioxide, methane, nitrous oxide, hydrofluorocarbon, perfluorocarbon, and sulfur hexafluoride (Statistisches Bundesamt, 2022a).

2.3. Sectoral targets and key steps to reach them

Germany is to become net GHG neutral [4] by 2045, as specified in the Federal Climate Protection Act of 2021. It aims to reduce industrial emissions by one-third by 2030, after the plateauing of emissions in the past two decades. This trajectory is in line with the European Green Deal emissions reduction plan (European Commission, 2019). Direct industrial emissions amounted to 181 Mt of CO_2 equivalent in Germany in 2021, excluding scope 2 emissions such as electricity from the power grid (UBA, 2022a), which corresponds to a 20% share of total GHG emissions in Germany.

In order to be able to meet the ambitious timetable for GHG reductions in the industrial sector and to give industry planning security for the necessary investments, the government must create clear and reliable long-term

[4] Definition of net greenhouse gas neutral: The balance between anthropogenic emissions of greenhouse gases from sources and the removal of these gases by sinks (KSG §2). For all practical purposes, "climate neutrality" is used as a synonym.

framework conditions for the decarbonisation of the industrial sector.

According to the *Umweltbundesamt – UBA* (German Environment Agency), the GHG emissions caused by industry can be divided into three groups:

- (1) Direct energy-related GHG emissions from the use of fuels to provide energy, e.g. process heat, steam or electricity (in industrial power plants);
- (2) Indirect energy-related GHG emissions from the upstream generation of the electricity or heat used, insofar as it is not generated in the company's own (industrial) power plants;
- (3) Direct process-related GHG emissions from the non-energy use of carbon-containing energy sources and other raw materials or from the process-related release of GHGs other than CO_2.

The different causes of GHG emissions generally require different approaches and mitigation measures in the various industrial sectors. The basic approaches are as follows:

The industrial sector could reduce its direct energy-related GHG emissions by increasing energy efficiency by switching to more energy-efficient technologies and using renewable energy in the form of electricity from renewable energy sources, e.g. for process heat generation.

Indirect energy-related GHG emissions can be reduced by converting more of the electricity grid to renewable energy, i.e. by phasing out electricity generation from coal and other fossil fuels. Moreover, improving the efficiency of energy conversion and use in industrial applications can help reduce indirect GHG emissions.

2.4. Overview of relevant energy legislation

At the national level, the German Federal Government and Ministries are implementing decarbonisation pathways through various laws and instruments. However, as an EU Member State, Germany's national climate strategies are significantly shaped by the framework of EU climate policies.

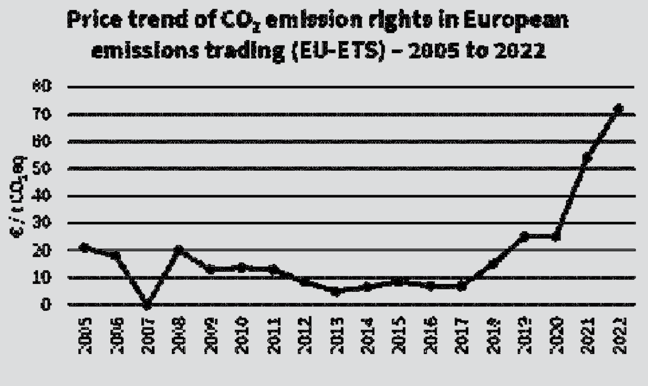
- The **Energy Efficiency Directive** promotes energy efficiency as a general principle of EU energy policy and sets rules and obligations for achieving the EU's 2020 and 2030 energy efficiency targets. Its key element is an energy efficiency target of at least 32.5% for 2030, compared to the 2007 projections for 2030. Thus the EU's overall energy consumption in 2030 should not exceed 1,023 Mt of oil equivalent.

Finally, direct process-related emissions can be reduced through fundamental process changes, i.e. by replacing the raw materials or products that cause emissions, e.g. by replacing coal with hydrogen as a reduction agent in steel production or by phasing out fluorinated gases. Carbon Capture and Utilisation or Storage (CCU/S) technologies are an alternative method to reduce process-related CO_2 emissions (see Excursus: Carbon Capture and Use/**Storage**).

In the short term, increasing the energy efficiency of industrial processes is the simplest measure to reduce emissions from the industrial sector (Bundesamt für Umwelt, 2022). The conversion of processes to renewable energy will be necessary to achieve the medium-term climate targets by enabling low-carbon production. Achieving these goals requires a set of laws and regulations governing and incentivising a quick transition to decarbonised industry.

EU Emissions Trading System

The power and certain industrial sectors are part of the **EU Emissions Trading System (EU ETS).** This system has been the EU's central climate protection instrument since its implementation in 2005. The EU ETS records emissions from more than 10,000 plants in the energy sector, European domestic aviation and industry, covering 36% of Europe's GHG emissions. The EU ETS operates on a cap-and-trade basis. A cap determines an annual CO_2 limit that may not be exceeded by installations subject to the ETS. Certificates are tradable on the market and the annual reduction of certificates is in line with the European climate targets. In its July 2021 "Fit for 55" package, the European Commission proposed a further tightening of the annual cap reduction from the current 2.2% to 4.2% per year, plus a one-time reduction of an as yet undetermined amount (likely in 2024). In Germany, a CO_2 price for the heating and transport sectors applies in addition to the EU ETS. The **Fuel Emissions Trading Act**, enacted in 2019, determines steady price increases within a predefined framework since 2021. From 2026, pricing will be set in a market. There is currently no link between the price and Germany's emission reduction targets.



- At the national level, the amended **Climate Protection Act** aims to ensure that the national climate protection targets are met (see above).

2.5. Status quo of energy consumption and trends in Chinese industry

To date, China is the world’s largest coal consumer and the country with the highest GHG emissions. It is estimated that in 2019, China emitted 30.6% of global CO_2 (Gesellschaft für Internationale Zusammenarbeit, 2021). China’s 2020 pledge to reach peak emissions before 2030 and pursue carbon neutrality by 2060 requires a profound and fundamental transformation of its energy system away from fossil fuels and towards a system based on renewable energy.

In 2021, China’s primary energy consumption amounted to 43,418 TWh. At over 54%, coal accounts for, by far, the largest share of China’s primary energy consumption. About 15% of primary energy consumption comes from renewables, with the largest share coming from hydropower (Ritchie, et al., 2020).

Looking at emissions by sector, the power sector is the country’s single largest GHG emitter, contributing 42% of CO_2 emissions in 2019. The industrial, manufacturing and construction sectors share 33% of total GHG emissions, with steel and cement production being the largest emitters (see **Error! Reference source not found.**). In 2020, C hina’s steel industry produced more than 1.1 Gt of steel and emitted 1.5 Gt of CO_2 equivalent, making it the largest industrial emitter of CO_2. Since 2010, steel production has increased by 67%. As of 2020, 80% of China’s steel is produced from iron ore, which is well above the global average of 60%. In 2021, the China Iron and Steel Association launched an initiative to encourage the iron and steel industry to peak carbon emissions ahead of schedule during the 14th Five-Year Plan period (2021–2025) (Natural Resources Defense Council, 2022; IEA, 2021a).

China’s cement industry has experienced rapid growth in recent decades. Cement production quadrupled from around 600 Mt in 2000 to around 2.4 Gt in 2020. Total CO_2 emissions from cement production amounted to 1.3 Gt in 2020, accounting for around one-third of China’s overall industrial emissions. China’s chemical industry is the largest in the world, with direct CO_2 emissions of 530 Mt in 2020. Industries other than the chemical, steel, and cement industries produced combined emissions of 740 Mt in 2020 (IEA, 2021a).

Coal is still key to fuelling China’s economy. To ensure a rapid decline in carbon emissions after 2030, China must take drastic action to decarbonise its energy system. Switching away from coal will be the main driver of emissions reductions. Electricity forms the backbone of the energy transition in the industrial sector, becoming the main energy carrier in the sector. The high share of heavy industry processes in China, which are difficult to electrify, is an additional challenge.

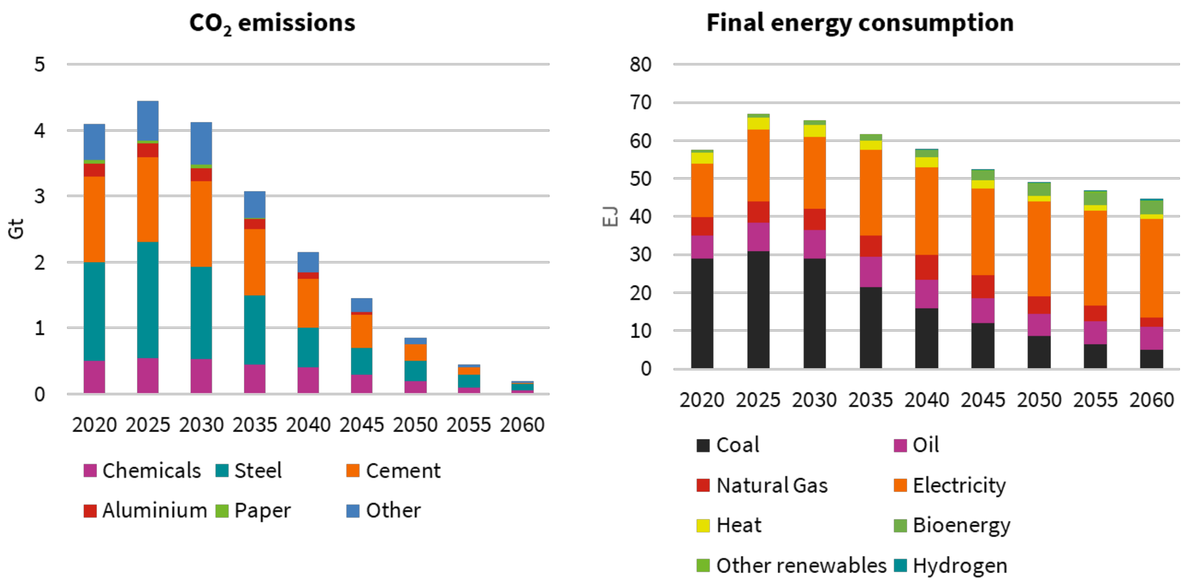


Figure 2: CO_2 emissions and final energy consumption in industry, China (IEA, 2021a).

3. The Energy Transition in German Industry

The energy transition in industry poses different challenges, which are presented in the following with a focus on energy efficiency, renewable energy generation and hydrogen and their roles in the transition.

Key elements of the energy transition in industry

The industrial sector has met its sectoral GHG emission reduction targets in 2021. However, energy demand (722 TWh in 2018) remains high and has decreased only slightly since 2000. The key elements for a successful energy transition of industry in Germany are improving energy efficiency and implementing new technologies based on renewable energies (dena, 2021).

In the dena pilot study (DPS), a model of how Germany can achieve its political climate protection targets in 2030 and 2045 was conducted in consultation with scientific institutes and stakeholders. There have been several climate neutrality studies in Germany. For the sake of simplicity, we refer only to the figures from one of the studies, the dena pilot study.

The future energy demand of the industrial sector will mainly be covered by hydrogen and electricity, both based on renewable energy sources. Therefore, meeting future energy demands requires a massive expansion of renewable energy sources and international partnerships (e.g. for hydrogen). The transition of industry is costly, as applying these green solutions requires high investment costs. Therefore, high costs and ensuring international competitiveness are the major challenges (dena, 2021).

3.1. Energy efficiency

The need to improve energy efficiency applies to both processes and materials. According to the DPS, process-related efficiency improvements have a high potential. If Germany does not realise this potential, energy demand will be at least 100 TWh higher in 2045 (projected energy demand with measures for 2045: 578 TWh). Efficiency can reduce emissions across all industrial sectors, but it is especially effective in cross-sectional technologies (e.g. pumps, motors, etc.). Detailed information on new technologies for the transition in the different sectors is described in Chapter 3.

The implementation and use of new, innovative and efficient technologies remain, in most cases, more expensive than continuing production with conventional technologies. Therefore, a rapid transformation and

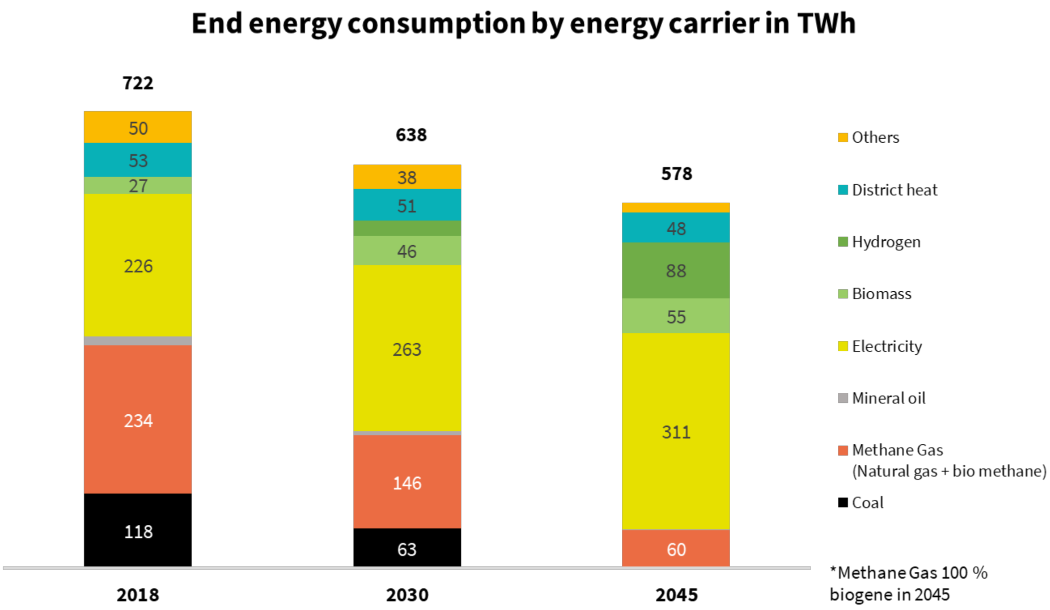


Figure 3: End energy consumption by energy carrier in industry (dena, 2021)

switch to new technologies require financial support (dena, 2021).

One useful instrument to accelerate the shift towards more efficient processes is the energy management system. This programme is already being implemented but is not yet mandatory. The energy management system is a certification system that guides companies to reduce their energy consumption and increase efficiency by measuring and analysing energy flows within the company, identifying potentials and implementing measures to increase the potential. The international standard for an energy management system is ISO 50001 (UBA, 2019).

In addition to increasing efficiency in the energy sector, efficiency savings are also possible in the production, design and processing of materials. This can be achieved, for example, through the reuse of materials, an extension of life cycles or lightweight construction.

3.2. Renewable electricity generation

Electricity is already the most important energy source in industry, and it is set to increase further as many processes will switch from fossil fuels to electricity, especially low-temperature process heat, such as steam, which is explained in more detail in Chapter 3. Electrification is already possible in many industrial sectors as an option for decarbonisation using power-to-heat or heat pumps. Green hydrogen and other synthetic fuels [5] are not yet available outside of pilot projects and will depend in the future on the expansion of renewable energy production and political support (dena, 2021).

The authors of the DPS expect a direct demand for electricity of 311 TWh in 2045 (in comparison to 2018: 226 TWh), plus a need for green hydrogen and its derivatives amounting to 242 TWh for energy and as material feedstock.

In addition to industry, the electrification of other sectors is necessary to achieve the political climate protection targets. Overall, this leads to an increase in electricity demand from 500 TWh in 2018 to 800–900 TWh in 2045. At the same time, half of the German electricity system is still based on conventional power plants. The share of renewable energies in gross electricity consumption was about 41.1% in 2021 (234 TWh). For 2045, the DPS expects an electricity supply from renewable energies of 750 TWh and a residual load supply of 65 TWh via hydrogen.

As mentioned in the previous section, the provision of electricity from renewable energies is a prerequisite for a successful transformation of industry to GHG neutrality. For this reason, Chapter 5 examines possible options for securing renewable electricity supply in industry (dena, 2021).

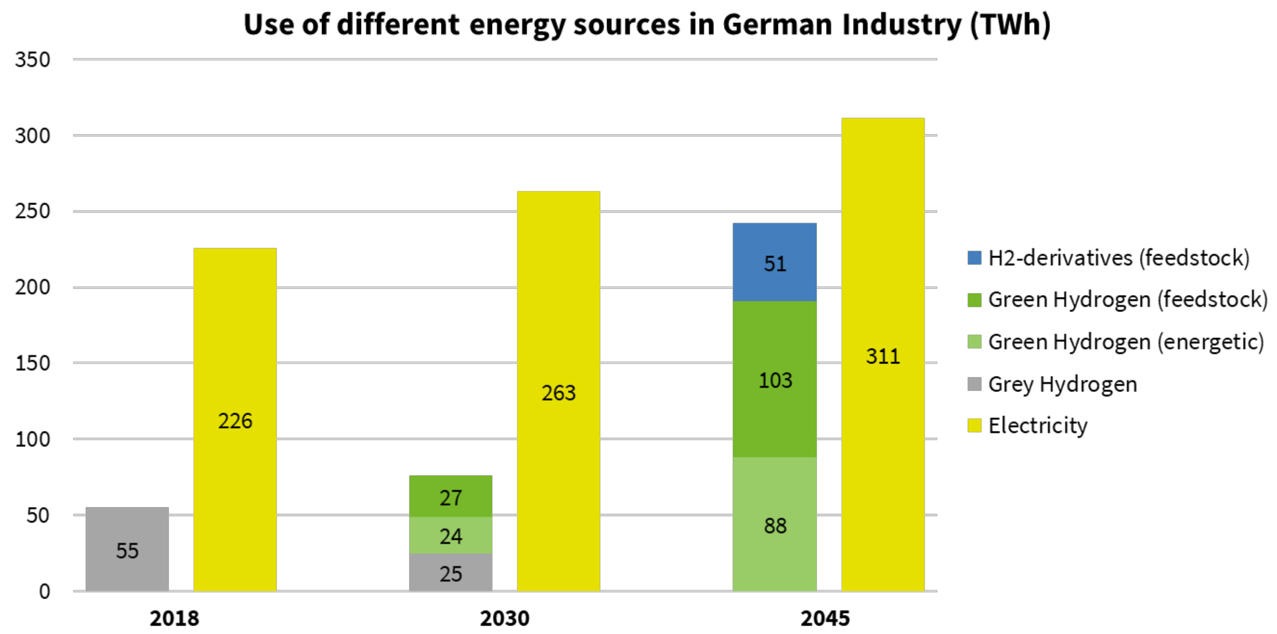


Figure 4: Consumption of synthetic energy sources and electricity in industry (dena, 2021)

[5] Definition of synthetic fuels: Gaseous and liquid energy carriers, including hydrogen, generated using power-to-X technologies based on renewable electricity (dena, 2021).

3.3. Hydrogen

Hydrogen plays a crucial role in the transformation of the energy system as a cross-sectoral technology. The use of hydrogen as a fuel is possible in various sectors and contributes to decarbonising areas where direct electrification is not possible. For example, this option exists in industrial processes to replace fossil fuels.

Currently, three processes are under discussion for the production of low-carbon hydrogen. Electrolysis uses renewable electricity, which can be completely emission-free, to produce green hydrogen. Other processes such as blue hydrogen (e.g. steam gas reforming of methane, gasification of coal with CCU/S) or turquoise hydrogen (methane pyrolysis, Kvaerner process – solid carbon capture) are never completely climate neutral due to emissions caused by methane leakage (Bauer, 2021).

Because of their possible cost advantage over green hydrogen, the latter could serve as a transition technology. The cost advantages are mainly due to the low price of gas until 2021.

The large-scale introduction of hydrogen in industry is dependent on imports and thus requires international partnerships that guarantee a supply of green hydrogen until 2045. The authors of the DPS expect a process- and energy-related hydrogen demand for industry of 51.5 TWh in 2030 and 191 TWh in 2045 (dena, 2021).

3.4. Challenges

The main challenges to achieving the necessary transformation in industry are cost, the current Technology Readiness Level (TRL)[6] of new technologies and the speed of transformation. In several industrial sectors, the necessary technologies are not ready for the market and are still at the research stage (Agora Energiewende, 2021). In order to achieve the necessary transformation to climate-neutral industry, these technologies must reach market maturity in line with the 2045 target.

In addition, there are challenges on the cost side, such as long amortisation periods, the lower cost of conventional fuels and technologies and the high cost of new technologies, which can limit competitiveness. Therefore, the necessary emission reduction targets may also increase the risk of carbon leakage[7], whereby companies relocate their production facilities to other countries with lower emission reduction targets (dena, 2021).

Further challenges then arise within such companies, which can be attributed to a lack of expertise and the availability of the technologies, but also a low priority within the company. Many new technologies require long investment cycles. Such cycles lead companies to refrain from investing due to uncertainties and a lack of short-term profit opportunities. A description of possible instruments for overcoming these challenges follows in Chapter 4.

Finally, carbon capture and utilisation/storage (CCU/S) is necessary to achieve negative emissions and offset the remaining residual emissions.

3.5. Excursus: Carbon Capture and Use/Storage

The Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) agree that the use of CCU/S is necessary to achieve the 1.5°C target (IPCC, 2022; IEA, 2021b). Especially regarding achieving negative emissions to offset unavoidable emissions and capturing process-related emissions in industry. In the case of CCS, the captured CO_2 is transported to suitable geological storage sites. The use of CCS is advisable for unavoidable emissions (e.g. the cement industry) or in combination with the use of biomass to generate negative emissions (BECCS[8]).

[6] Definition of TRL: Scale for the systematic assessment of the development status of new technologies. The value range extends from 1 to 9:
- TRL 1: Observation and description of the functional principle (8–15 years)
- TRL 2: Description of the use of a technology
- TRL 3: Evidence of the functioning of a technology (5–13 years)
- TRL 4: Experimental setup in a laboratory
- TRL 5: Test setup in an operational environment
- TRL 6: Prototype in an operational environment
- TRL 7: Prototype in use (1–5 years)
- TRL 8: Qualified system with proof of functional capability in an operational environment
- TRL 9: Qualified system with proof of successful use (ESA, 2022; NASA, 2022)

[7] Definition of carbon leakage: Carbon leakage is the risk of production being relocated abroad to countries with lower environmental standards and resulting in higher emissions due to excessive costs at the previous place of production because of decarbonisation measures.

[8] Definition of BECCS – Bioenergy Carbon Capture and Storage: The use of CCS in industrial facilities that use

The chemical industry and synthetic fuels, e.g. kerosene, also require carbon as a feedstock, for which Carbon Capture and Utilisation (CCU) technologies can be used. Much of the products in the chemical industry are based on crude oil as feedstock. The carbon used in these products remains in the product until the end of its life. In the future, carbon will continue to be needed for these products. In order for the chemical industry to stop producing emissions by using crude oil as a feedstock, it needs green hydrogen and CO_2. Methanation, methanol synthesis and Fischer-Tropsch synthesis are the three syntheses that make it possible to replace crude oil as a feedstock (see Chapter 4.3).

In shipping and aviation, a different problem arises. In these sectors, there is still a need for fuels containing carbon. This is due to the lack of alternatives. Other technologies, such as batteries or the use of hydrogen, are not applicable due to their weight (battery), energy density and the resulting storage volume (hydrogen) (Fraunhofer-Institut UMSICHT, 2020). For this reason, the use of carbon-containing fuels will continue in the future. The problem here is that it is not possible to capture the CO_2 produced. In order to achieve climate neutrality in the long term, this carbon must come from either biomass, Direct Air Capture (DAC) or the material recycling of plastics produced from biomass or DAC.

A climate-neutral energy system, therefore, depends on functional carbon management based on CCU/S, especially in technical cycles. The transport and storage of CO_2 depend on public acceptance. In Germany, concerns about possible health risks due to leakage have led to reservations about this technology. That is why it is important to have a regulatory framework that takes the public's concerns seriously and incorporates them (Fischedick, 2015).

If public acceptance is achieved, there is still a need for an infrastructure that enables transport and storage. CO_2 infrastructure planning should include electricity, gas and hydrogen infrastructures. Hydrogen is especially needed in combination with CO_2 for CCU in the chemical industry and for the production of synthetic fuels. Joint planning can therefore lead to synergies. In addition, industry clusters should be included, as they can lead to economies of scale due to the comparatively higher quantities of CO_2, which has a cost-reducing effect. Large-scale transport options include ships and pipelines. In general, transportation and storage still face the following challenges: risk management, financing (CO_2 market) and lack of experience in transportation with large ships (10 Mt) (elementenergy, 2018).

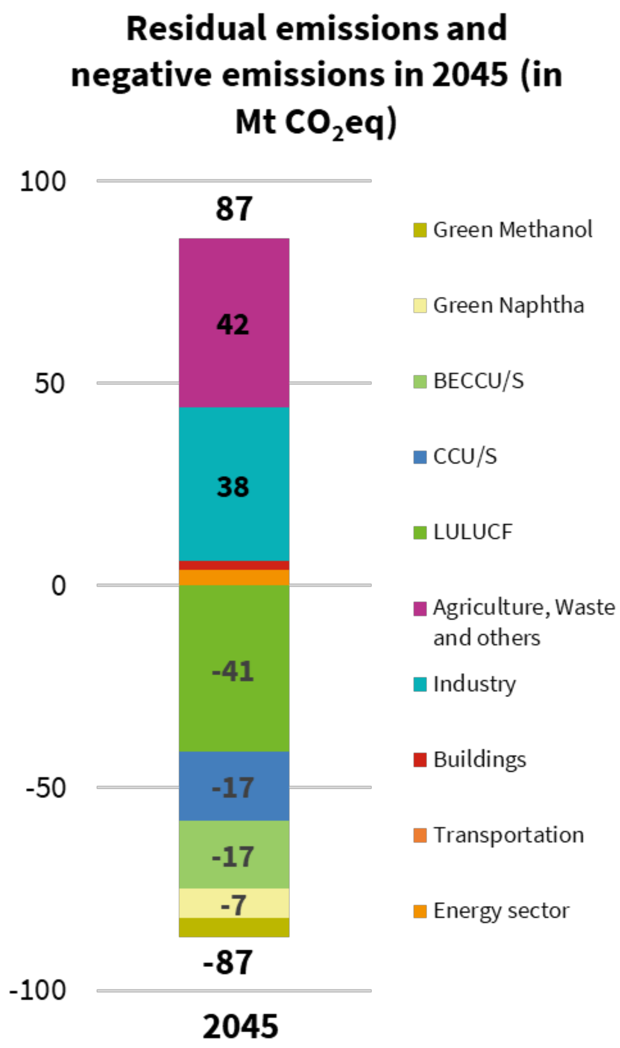


Figure 5: Residual and negative emissions in Germany according to the DPS in 2045 (dena, 2021)

Within the framework of the DPS, residual emissions[9] of 87 Mt of CO_2 have been assessed for Germany in 2045. It is assumed that negative emissions of 41 Mt of CO_2 are achievable in the Land Use, Land-Use Change and Forestry (LULUCF) sector in line with national targets. The reduction and compensation of the remaining

biomass as an energy source. The use of sustainable biomass according to the criteria of (WGBU, 2009) can lead to negative emissions.

[9] Residual emissions: Residual emissions are emissions (especially methane, nitrous oxide and process emissions) in agriculture, waste management and industry that are hard to reduce and continue to occur despite the decarbonisation of the energy system.

emissions can be achieved by technical solutions using CCU/S for process emissions and in combination with bioenergy (BECCU/S). The study estimates an emission reduction potential of 17 Mt of CO_2 using CCU/S. For the remaining emissions, it is necessary to offset them with negative emissions. The study shows that at least 24 Mt of CO_2 must be captured in 2045 from German industry and then placed in geological storage. Furthermore, 10 Mt of CO_2 will be transferred to use via CCU. By using BECCS, negative emissions of 17 Mt of CO_2 are achievable (dena, 2021).

In comparison, in the IEA scenario analysis (2021) for achieving China's climate policy targets, the CCU demand for China's chemical industry alone is 200 Mt of CO_2 in 2060 (IEA, 2021a). For 2060, the IEA (2021) projects an annual CCU/S capacity of about 2.5 Gt of CO_2 per year (IEA, 2021a). Overall, the share of CCU/S is expected to be higher due to the use of coal in industry, which leads to higher emission volumes and capture rates.

3.6. Excursus: Consequences of the gas and energy crisis in Europe

Legislative reaction

The gas supply is important for Germany. In 2019, 48.2% of German households used gas-fired central heating for their homes. Similarly, gas is the most important energy source in industry: the sector consumed 325 TWh in 2020, accounting for 31.2% of total consumption (Statistisches Bundesamt, 2022b).

The crisis in Ukraine and the subsequent halt in Russian gas supplies to Western Europe have triggered an energy and gas crisis in Europe, putting European and, in particular, German energy policy under scrutiny. The EU and Germany are making efforts to diversify the energy supply and reduce gas demand. Germany has implemented legislative processes to ensure the security of supply and accelerate the deployment of renewable energy. The electricity supply is adequate and secure, but the supply of gas, mainly for heating and industry, is not (Bundesministerium für Wirtschaft und Klimaschutz, 2022a).

The German government has implemented the "Substitute Power Plant Standby Act" and the "Energy Security Act", which aim to remove gas-fired power plants from the power market to save gas in electricity production and to expand the responsibilities of the Federal Network Agency. The limited gas supplies are therefore prioritised for heating in households, public buildings and industry, where replacement is more difficult than for power generation.

In industry, in particular, the short-term replacement of gas (see Chapter 2.3 Sectoral targets and key steps to reach them) is difficult. Significant decreases in production due to soaring gas prices can already be observed after the interruption of Russian gas supplies through the Nord Stream 1 pipeline in August 2022.

Safeguarding gas supplies is, therefore, an immediate priority for the German government. Measures include:

- Constructing Liquefied Natural Gas (LNG) terminals for the short- and medium-term diversification of gas supplies
- Filling gas storage facilities
- Safeguarding the functioning of the gas market in order to maintain gas supplies (takeover of Uniper, margination programmes)
- Gas savings: the EU has agreed on a gas savings target of 15%, and Germany set a target of 20%
- A range of energy efficiency measures

Moreover, the German government has enacted gas price subsidies to ease the financial pressure on German industry and households. For industrial consumers, the basic quota should correspond to 70% of consumption in 2021. For this, a gross procurement price of 7 ct/kWh is set. Above a threshold of 70%, the agreed market price will be due (Bundesministerium für Wirtschaft und Klimaschutz, 2022b). This regulation could affect around 25,000 companies that would be allowed to market subsidised gas quantities they do not consume. This measure is intended to encourage energy saving. The conditions for receiving the subsidy are the preservation of the production site and the conversion to climate-friendly production methods.

Reaction in industry:

Soaring energy prices and insecure gas supplies impact current production as well as medium- to long-term strategic planning in industry.

In the short to medium term, industry can respond to high natural gas prices in part by switching to other energy sources and raw materials (petroleum products such as heating oil, Liquid Propane Gas (LPG) and naphtha as well as biomass). The accelerated electrification of steam supplies makes it possible to reduce the use of gas. Additionally, production cutbacks and imports of energy-intensive intermediate products (e.g. ammonia) are to be expected. According to some estimates, industrial gas use could be reduced by 50% by 2025 (MCC, 2022).

In the first half of 2022, German households and industry reduced gas use by almost 15% compared to the same period in 2021, translating to gas savings of 80 TWh. However, most of this decrease is the result of savings in industry, which reduced its gas consumption by 17% within the first nine months of 2022 compared to the same period in the last 5 years (MCC, 2022).

This reduction is due to energy efficiency measures, electrification, switching to alternative fossil energy sources, changes in production processes, but also a reduction in production. In the medium to long term, industrial companies will have to replace gas and other fossil energy sources with renewable energy and improve energy efficiency to reduce final energy demand and reach pre-war production capacities. This transformation is not di14imilar to the transition in industry described in Chapter 3, but it will need to be further accelerated.

3. Overview of the Most Important Energy Transition Technologies in Industry

As described in the previous chapters, industry in Germany must undergo a fundamental change to achieve the targets set in the Federal Climate Act, in particular, a shift to new technologies. The most important technologies in the cement, steel, chemistry, non-ferrous metals and pulp & paper sectors, as well as cross-sector technologies, are described in detail in the following. For a better presentation of the individual technologies, an overview of the current and future (in 2045) technologies and energy carriers used in Germany, as well as technology fact sheets, are available at the end of the chapter (see Figure 7).

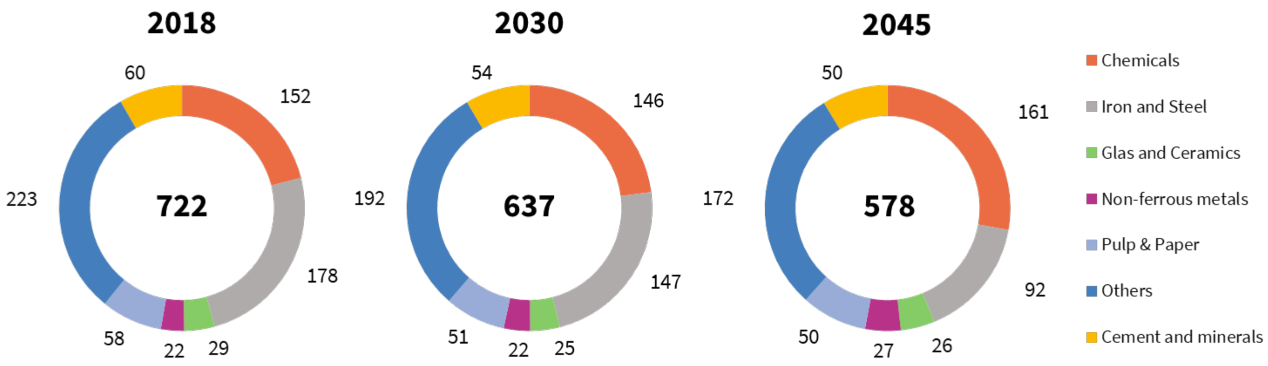


Figure 6: Final energy consumption (TWh) for different industrial sectors (dena, 2021)

4.1. Cement industry

The cement industry accounts for around 2.5% of emissions in Germany (UBA, 2020).

The decarbonisation process of the cement industry differs from other industries in particular due to the high proportion of process emissions. In the cement industry, unavoidable CO_2 emissions occur during the combustion of limestone ($CaCO_3$ -> CaO + CO_2). These process-related emissions account for about 65% of total emissions in cement production (Johnsson, 2020). The use of CCU/S is necessary to reduce these emissions.

The remaining process emissions are energy-related. The elimination of this share of emissions is possible partly or completely through electrification with climate-neutral electricity or the use of climate-neutral fuels such as sustainable biomass, green hydrogen or synthetic gas. The use of climate-neutral fuels in combination with CCU/S offers the potential of achieving negative emissions. Various studies show that using sustainable biomass as a fuel results in negative emissions (Briones-Hidrovo, 2022; Garcia-Freites, 2021).

The most important technologies for decarbonisation are presented below. In Germany, it is assumed that there will be no fundamental technological developments for conventional processes. Decarbonisation is based on a combination of various technical measures. Efficiency measures to reduce energy consumption and the use of climate-neutral fuels can completely reduce energy-related emissions. The use of CCS is necessary for process-related emissions. Generally speaking, there are two processes in the cement industry: oxyfuel and post-combustion. Pre-combustion, as practised in the Integrated Gasification Combined Cycle (IGCC) in power plants, for example, is not possible due to the emissions generated in the cement process (Fischedick, 2015).

Post-combustion processes capture the CO_2 after the actual process. The advantage is the possibility of retrofitting if the necessary space is available (Fischedick, 2015) (see Figure 9, Figure 8, Figure 10 and Figure 11).

4.2. Steel industry

In Germany, the iron and steel industry accounts for 25% of energy demand in the industrial sector; therefore, it is an essential part of the decarbonisation strategy.

The steel industry distinguishes between primary and secondary steel in the production processes. In Germany, around two-thirds of steel production is primary steel. Primary steel is produced via the blast furnace route, using coking coal as a reducing agent and energy source. The remaining production is secondary steel by recycling steel scrap via an electric arc furnace using electricity. This process is more energy efficient, but it does not produce high-quality steel products. In addition, production is limited by the availability and quality of scrap (dena, 2021).

In China, the share of primary steel is 80%. In future, the share of secondary steel is expected to increase (IEA, 2021a).

In the production of steel via the blast furnace route, process-related emissions are generated by the reduction of iron ore (Fe_2O_3 and Fe_3O_4) to liquid iron. The resulting flue gas is reused in the process and leads to CO_2 emissions. After the blast furnace process, the removal of carbon from the crude iron by adding oxygen leads to additional process emissions. For complete decarbonisation, it is necessary to remove not only energy-related emissions but also process-related emissions (Agora Energiewende, 2021).

The following paragraphs present various processes to reduce CO_2 emissions. The DPS expects that primary steel production in Germany will be based entirely on direct hydrogen reduction by 2045 (dena, 2021) (see Figure 12).

In addition to the direct hydrogen reduction process, two other processes will be market ready by 2040. These processes will probably not play a role in achieving the climate protection targets in Germany. Both processes continue to use fossil fuels (coal or natural gas) via CCU/S (see Figure 13, Figure 14).

4.3. Chemical industry

As a large share of products in the chemical industry need carbon as a feedstock, the decarbonisation of the chemical industry requires new processes that enable climate-neutral production (VCI, 2019). The existing and future feedstock materials used in Germany for the most important chemical products (methanol, ammonia, olefins & aromatics and chlorine) are described in the following.

A major difference between the German and Chinese chemical industries is the different feedstock (raw material) used to produce chemicals. In Germany, chemicals are mainly produced via natural gas and naphtha, whereas the main feedstock in China is coal. As a result, naphtha-based technologies play a minor role in China's chemical industry. In contrast, the Methanol-to-Olefin (MTO) route is already of significant importance (IEA, 2021a).

Methanol is currently produced by steam reforming of methane, partial oxidation of crude oil in Germany or gasification of coal in China. In future, climate-neutral methanol production will be possible by synthesising hydrogen and CO_2 or gasifying biomass. For Germany, the DPS assumes that 60% of methanol is produced from green hydrogen and 40% from biomass gasification (dena, 2021).

Currently, ammonia is produced using the Haber-Bosch process. The raw materials are hydrogen from methane and nitrogen steam reforming. To decarbonise it, hydrogen from water electrolysis is used, so the feedstock materials are electricity and hydrogen. Hydrogen is supplied either by imports or electrolysers close to the plant. For 2045, the DPS assumes that ammonia will be produced entirely by electrolysis (green hydrogen), which, in combination with the electricity-based Haber-Bosch process, leads to climate neutrality (dena, 2021).

The production of olefins and aromatics In existing industrial plants is based on the steam cracking of fossil naphtha. The production of fossil naphtha requires crude oil as feedstock. Olefins and aromatics are hydrocarbon compounds. It is not possible to replace carbon with other feedstock materials. Two processes are being considered for future production, which will be explained in more detail later (see Figure 16 and Figure 15). Both processes require hydrogen and CO_2 as feedstock. The hydrogen can either be imported or supplied via electrolysis. Possible sources for CO_2 are biomass, waste, captured CO_2 from other industrial processes (e.g. the cement industry) and air (Direct Air Capture – DAC).

In today's industrial installations, chlorine production is based on electricity. No changes are expected in the future. Only the plant process will change, with the more efficient diaphragm process replacing the still widespread amalgam process (VCI, 2019).

Green naphtha production requires hydrogen and CO_2 as feedstock. Naphtha can be supplied by Fischer-Tropsch synthesis and water-gas shift reaction ($H_2 + CO_2 <-> H_2O + CO$) (see Figure 17). Within the framework of the DPS, it is assumed that 60% of aromatics & olefins will be produced using the methanol-to-olefins/aromatics process and 40% by steam cracking of green naphtha (dena, 2021).

In summary, methanol and synthesis gas based on green hydrogen and non-fossil CO_2 are necessary as feedstock for decarbonisation.

4.4. Pulp & paper industry

In the pulp and paper industry, emissions stem from the use of energy, mainly for steam generation. Due to the low temperature level of the necessary heat supply, heat pumps and electric boilers are possible options, similar to the chemical industry (see Figure 23). In future, other technologies for using "black liquor" (an energy- and lignin-rich by-product of cellulose production) may become more relevant (see Figure 18 and Figure 19). Black liquor, which accumulates in production, is currently used in recovery boilers to generate energy (Nurdiawati, 2021).

4.5. Glass industry

Glass is produced via melting in a furnace using gas as an energy source. Several options are available for decarbonisation in the future. Firstly, production can take place in an electric furnace. Another option is to use hydrogen as an energy source. Hybrid furnaces (electricity + hydrogen) are also a possible option for the future. A small amount of process emissions occurs during the production of glass, which could be avoided by changing the raw materials from carbonates to oxides (dena, 2021).

4.6. Non-ferrous metal industry

There are two main processes in aluminium production. First, there is the conversion of bauxite to alumina (Al_2O_3) via the Bayer process followed by the conversion of alumina into aluminium (Chan, 2019). Primary aluminium is produced using the Hall-Héroult process. In this process, electricity is required as an energy source. During production, process emissions occur at the anode, as the anode consists of carbon and reacts with the oxygen produced during the process, forming CO_2. Furthermore, aluminium can be recycled. The process is significantly more efficient (5% of the energy consumption of the primary process) and is carried out in smelting furnaces using gas as an energy source (Mobarakeh, 2022) (see Figure 22, Figure 21 and Figure 20).

There are two possible processing routes for copper production. The first is the pyro-metallurgical route (80%), and the second is the hydro-metallurgical route (20%). During the copper production processes, there are no process emissions. Therefore, decarbonisation is possible by switching from fossil fuels to climate-neutral electricity.

4.7. Efficient cross-sectoral technologies

Across the entire industrial sector, there is an opportunity to reduce energy demand by using efficient technologies. In Germany, the use of these technologies could reduce energy demand by 100 TWh, with an existing energy demand of 722 TWh in 2018. This reduction is due to the switch to energy-efficient compressors, motors and other technologies.

In all industrial sectors, the efficient provision of process heat plays an important role in decarbonisation.

In Germany, process heat accounts for 22% of final energy consumption (510 TWh). The use of power-to-heat technologies is possible, especially for temperatures up to 500°C, via electrode boilers and heat pumps. Compared to hydrogen, these technologies not only offer better efficiency but can also be used to make the power system more flexible (Demand Side Management – DSM). With a high share of renewable energy in the electricity mix, these technologies can be added selectively to take advantage of low electricity price costs. At the same time, if the supply of renewable energy is low, the load can be reduced and the use of expensive power plants at peak times can be avoided (Agora Industrie & Future Camp, 2022) (see Figure 23). In addition, the use of waste heat offers great potential. It can be used in various processes, such as a heat source in industrial processes, as well as input for heat pumps or district heating. For this, the necessary preconditions must be taken into account. For example, its use in district heating networks requires that the networks be adapted to use the waste heat (dena, 2021).

Products		Status Quo		New	
		Process/technology	**Main energy carriers**	**Process / technology**	**Main energy carriers**
Aluminum	Primary	Hall-Heroult, Point feeder	Electricity	Use Inert anode	Electricity
	Secondary	Gas-melting furnace	Natural gas	Hybrid / electric furnace	Electricity, Hydrogen
Ammonia		Haber-Bosch, Steam Methane Reforming (SMR)	Gas (energetic + material)	Haber-Bosch with Green Hydrogen	Hydrogen resp. electricity for electrolysis
Aromatics & Olefins		Steam cracking	Fossil Naphtha (material)	▪ Methanol to Olefins/Aromatics ▪ Steam cracking, green Naphtha	▪ Electricity ▪ PtL (material)
Cement		Semi-dry process	▪ Alternative fuels (i.e. waste) ▪ Hard coal	Dry process	▪ Alternative fuels ▪ Biomass
		Dry process			
Copper	Primary	Melting and refinery	▪ Electricity ▪ Gas ▪ Hard coal	Conversion from fossil fuels to electricity and hydrogen	Electricity, Hydrogen
	Secondary	Copper recycling			
Glass		Classic melting tank	Natural gas	▪ Hydrogen melting tank ▪ Electric melting tank ▪ Hybrid furnace	Electricity, Hydrogen
Methanol		Synthesis: ▪ Partial oxidation of heavy fuel oil ▪ Steam Methan Reforming	Heavy fuel oil/ Natural gas	Synthesis: ▪ Hydrogen/CO_2 ▪ Gasification of biomass	Hydrogen, electricity, biomass
Pulp & Paper		• CHPs • Blackliquor recovery boiler	Natural gas	▪ Electrification of heat consumption (heat pumps) ▪ Black liquor gasification ▪ Lignin Extraction	Electricity
Steel	Primary	▪ Blast furnace route/Basic oxygen furnace ▪ Steel processing with coke gas/gas	Coking coal	▪ Direct reduction + electric arc furnace ▪ Steel processing with hydrogen	Hydrogen, electricity
	Secondary	Electric arc furnace	Electricity	Electric arc furnace	Electricity

Figure 7: Overview of current and future technologies in key industrial sectors

CCU/S with Amine Scrubbing

Possible Availability

- 2025 – 2030

Emission reduction potential

- > 90%
- 100% when climate neutral fuels are used

State of development

- Demonstration plant
- (TRL 6-7)

CO_2 avoidance costs

- 60 – 170 $/t CO_2

Technology description

The amine scrubbing post-combustion process is already used on an industrial scale in power plants and other industrial processes. The process uses a chemical solvent (MEA) to capture CO_2. In Norway, the first demonstration plant for capturing emissions from cement production is in planning and is expected to be operational in 2024 (HeidelbergCement, 2022). Industrial use is expected to be available in the years 2025–2030 (Nuridawati, 2022). The dena pilot study assumes that this process will be used to decarbonise the German cement industry (dena, 2021). The estimated capture rate is 90%.
The CO_2 avoidance costs for this technology are between $60 and $170 per tonne of CO_2 (Leeson, 2017).

Figure 9: Cement industry – Technology letter: CCU/S with amine scrubbing

CCU/S with Carbonate Looping

Possible Availability

- 2030 – 2040

Emission reduction potential

- > 90%
- 100% when climate neutral fuels are used

State of development

- Demonstration plant (TRL 6 - 7)

CO_2 avoidance costs

- 14 – 70 $/t CO_2

Technology description

This post-combustion process is under development (TRL 6–7) and is mentioned because of its synergy with the raw materials used in cement clinker production (CLEANKER, 2020; Global CCS Institute, 2021). The carbonate looping process uses CaO to capture CO_2. Commercial application is expected between 2030 and 2040 (Moborakeh, 2022; Nurdiawati, 2022). The reduction potential is 90%. Avoidance costs range from $14 to $70 per tonne of CO_2 (Leeson, 2017).

Figure 8: Cement industry – Technology letter: CCU/S with carbonate looping

CCU/S with Oxyfuel-process

Possible Availability

- 2025 – 2030

Emission reduction potential

- > 90%
- 100% when climate neutral fuels are used

State of development

- Demonstration plant (TRL 6 - 7)

CO_2 avoidance costs

- 50 – 65 $/t CO_2

Technology description

In this process, the combustion processes are carried out using a mixture of pure oxygen and recycled CO_2. The advantages are higher CO_2 purity in the exhaust gas stream and easier capture of the CO_2, enabling capture rates of up to 90%. The process can be retrofitted to existing installations. However, changes in process management are required. Commercial use is expected as early as 2025, assuming optimal technological development (Mobarakeh, 2022; Nuridawati, 2022). The cost of CO_2 avoidance is between $50 and $65 per tonne of CO_2 (Leeson, 2017).

Figure 10: Cement industry – Technology letter: CCU/S with Oxyfuel process

Alternative binding materials

Possible Availability
- 2020 – 2030 (depending on product)

Emission reduction potential
- Up to 53%

State of development
- Magnesium silicates (TRL 3)
- Carbonate calcium silicates (TRL 7 – 8)
- Alkali activated binders (TRL 9)

Costs
-

Technology description

The use of alternative binders to replace clinker, as well as resource-efficient concretes, can save energy and reduce emissions. An assessment of the market maturity and emission reduction potential of alternative binders is currently not possible due to the heterogeneous stages of development. Reduction potentials of up to 53% are feasible (Agora Energiewende, 2021).
Industrial use depends on the product and is expected between 2020 and 2030 (Moborakeh, 2022; Nuridawati, 2022). Costs are not estimated due to the heterogeneity of the different binders and their state of development.

Figure 11: Cement industry – Technology letter: Alternative binding materials

Direct reduction with Hydrogen (H_2 – DRI)

Possible Availability
- Currently in operation (with Natural gas)
- 2025 – 2030 (with H_2)

Emission reduction potential
- 97%
- 100% if biomass or synthetic gas are used for foaming slag

State of development
- H_2 DRI: Demonstration plant (TRL 5 - 7)
- Natural Gas DRI: Commercial plant (TRL 8 – 9)

CO_2 abatement costs
- 2030: 60 €/t CO_2 with use of natural gas
- 2050: 85 – 144 €/t CO_2

Technology description

In the direct hydrogen reduction and electric arc furnace smelting process, pelletised iron ore is reduced using hydrogen. The resulting sponge iron can then be smelted into crude steel in an electric arc furnace. By using green hydrogen, the process is almost climate neutral. A residual amount of emissions is produced by providing a carbon carrier for slag foaming. If the carbon carrier is biomass or synthetic gas, the process is climate neutral.
Commercial installations are in the planning stages. In addition to hydrogen, the planned installations use metallurgical gases and natural gas as reducing agents (Agora Energiewende, 2021). Industrial production is planned at the earliest between 2025 and 2030 for a fully hydrogen-based plant (Mobarakeh, 2022; Krook-Riekola, 2022; Nuridawati, 2022).
As described above, earlier use is possible if natural gas is first used instead of hydrogen and then the proportion of hydrogen is gradually increased. CO_2 reductions of 66% can already be achieved by using natural gas.
The conversion involves additional costs, which depend especially on the price of electricity and hydrogen. Agora Energiewende (2021) assumes CO_2 reduction costs of $60 to $99 per tonne of CO_2 for 2030 (Agora Energiewende 2021).

Figure 12: Steel industry – Technology letter: Direct reduction with hydrogen (H_2–DRI)

HIsarna® –process in combination with CCS

Possible Availability

- 2030 - 2035

Emission reduction potential

- 86%

State of development

- Pilot plant (TRL 5 - 7)
- Without CCS (TRL 7 – 9)

CO2 abatement costs

- 2030: -
- 2050: 25 – 45 €/t CO_2

Technology description

The HIsarna® process in combination with CCS continues to use coal as an energy source and reducing agent. Instead of a blast furnace, a special reactor is used. Iron ore is injected directly into the reactor, which reacts with pure oxygen instead of air and coal. The product is a CO_2-rich waste gas, which is more suitable for capture. The process can achieve a capture rate of 86% (Agora Energiewende, 2021). The technology is expected to be market-ready between 2030 - 2035. The technology has limited relevance for Germany due to its late availability (Mobarakeh, 2022; Krook-Riekola, 2022; Nuridawati, 2022).
The advantage over direct reduction are the lower costs. For 2050, Agora Energiewende (2021) expects CO_2 abatement costs of 25 - 45 €/t CO_2, resulting in specific additional costs of 9 – 16% (Agora Energiewende, 2021).

Figure 13: Steel industry – Technology letter: HIsarna – Process in combination with CCS

CCU of metallurgical gases from blast furnace route

Possible Availability

- 2025 – 2030

Emission reduction potential

- 50 - 63%

State of development

- Pilot plant (TRL 4 – 5)
- Without CCU/S (TRL 7)

CO_2 abatement costs

- 2030: 231 – 439 €/t CO_2
- 2050: 178 – 379 €/t CO_2

Technology description

The process uses the captured CO_2 from metallurgical gases from blast furnaces to produce valuable chemical substances. A retrofit of the technology is possible to blast furnaces and can be used from 2025 at the earliest. The production of the chemicals has a high electricity demand. For this reason, the potential savings should be considered over the entire life cycle. The emission reduction is between 50 and 63% (Agora Energiewende, 2021).
The technology is to be considered a transitional technology and thus has a low relevance for the achievement of the German climate protection targets, since the ramp-up of direct reduction with hydrogen has to be started at an early stage (2025 - 2030) (Mobarakeh, 2022; Krook-Riekola, 2022; Nuridawati, 2022).
Agora Energiewende (2021) expects CO_2 abatement costs of 231 - 439 €/t CO_2 in 2030. This leads to specific additional costs of 63 - 119%. The high costs are a result of the inclusion of the German industry and electricity prices in the study (Agora Energiewende, 2021).

Figure 14: Steel industry – Technology letter: CCU of metallurgical gases from the blast furnace route

Methanol-to-Olefins/-Aromatics process

Possible Availability

- 2025 - 2030

Emission reduction potential

- 100%

State of development

- MTO (TRL 8 - 9)
- MTA (TRL 6)

CO_2 abatement costs

- 2030: 160 – 355 €/t CO_2 (MTO)
- 2050: 84 – 515 €/t CO_2 (MTO)
- 2050: 122 – 615 €/t CO_2 (MTO / MTA weighted average)

Technology description

In this process, methanol is used as feedstock for the production of olefins and aromatics, instead of fossil naphtha. For a climate-neutral process, the methanol must be produced by green hydrogen and CO_2 (Agora Energiewende, 2021). Assuming optimal technology development, large-scale use could be possible between 2025 and 2030 (Krook-Riekola, 2022). The reduction potential is 100% if the CO_2 is provided from non-fossil sources such as waste, sustainable biomass or CO_2 from air (DAC).
The cost assumption is highly dependent on the development of hydrogen and electricity prices. For this reason, Agora Energiewende (2021) calculates average abatement costs of 122 - 615 €/t CO_2 for the two processes. This results in specific additional costs of 45 to 277% (Agora Energiewende, 2021).

Figure 16: Chemical industry – Technology letter: Methanol-to-olefins/-aromatics process

Chemical Recycling (gasification and pyrolysis)

Possible Availability

- 2025 – 2030

Emission reduction potential

- 100%

State of development

- Demonstration plant (TRL 6 – 7)

CO_2 abatement costs

- 2030: -58 – 60 €/t CO_2 (non-integrated pyrolysis, depending on naphtha price)
- 2050: 11 – 49 €/t CO_2 (pyrolysis: including electric steam cracker and MTO)

Technology description

Through chemical recycling, the conversion of plastic into feedstock (synthesis gas: H_2 + CO, pyrolysis oil) for industry is possible. The conversion can be accomplished by two processes, which lead to different products and applications in industry. First, plastic waste can be converted into synthesis gas (H_2 + CO) by gasification, which serves as a starting material for the production of methanol and naphtha. Second, there is the option of the conversion of waste into oily liquids via pyrolysis. Oily liquids can be further processed in a steam cracker, reducing the use of fossil naphtha (Agora Energiewende, 2021). Both processes have a high level of technology development (TRL 6-7), which means that large-scale use can be expected from 2025 to 2030 (Krook-Riekola, 2022). The reduction potential is 93% if renewable energy is used and as long as the carbon remains in cycle.
Chemical recycling generates CO_2 abatement costs of 11 - 49 €/t CO_2. Within Agora Energiewende (2021), this results in specific additional costs of 6 - 25% (Agora Energiewende, 2021).

Figure 15: Chemical industry – Technology letter: Chemical recycling (gasification and pyrolysis)

Electrification of steam cracker

Possible Availability

- 2030 - 2040

Emission reduction potential

- 100%

State of development

- Laboratory phase (TRL 1 - 3)

CO_2 abatement costs

- 2030: 73 – 121 €/t CO_2
- 2050: 11 – 49 €/t CO_2

Technology description

Olefins and aromatics are currently supplied by steam cracking of naphtha. This process takes place at temperatures of 600 - 900 °C and uses fossil fuels. To decarbonise energy-related emissions, the electrification of the heat supply becomes necessary. The reduction potential is 100% using climate-neutral electricity. It is currently assumed that large-scale installations will be available between 2035 and 2045. For 2050, Agora Energiewende (2021) expects CO_2 avoidance costs of 11 - 49 €/t CO_2. This leads to an increase in specific costs of 15 - 18% (Agora Energiewende, 2021).

Figure 17: Chemical industry – Technology letter: Electrification of steam cracker

Black liquor gasification

Possible Availability

- 2020 - 2025

Emission reduction potential

- 10%

State of development

- Commercial plant (TRL 8 – 9)

Costs

- Inital investment cost difference: 300 – 500 €/t annual capacity

Technology description

Black liquor gasification is a technique for the generation of surplus electricity or biofuels. The process converts black liquor (energy- and lignin-rich by-product in cellulose production) into inorganic compounds (mainly sodium and sulphur). This makes it possible to recover combustible materials and flue gases, especially syngas (H_2 + CO). Currently, black liquor is used in recovery boilers (production of heat or electricity). The advantages of the described process are the higher efficiency as well as greater end-use flexibility (syngas to fuels, chemicals, etc.). The technology is expected to reach market readiness between 2020 and 2025. The initial cost difference of the investment of the technology is 300 - 500 €/t annual capacity (Chan, 2019).

Figure 18: Pulp & paper industry – Technology letter: Black liquor gasification

New drying techniques

Possible Availability

- 2020 - 2025

Emission reduction potential

- 20%

State of development

- Pilot plant (TRL 5 - 7)

Costs

-

Technology description

In the pulp & paper industry, the process of drying in paper mills is the major energy-consuming process. For this reason, there is an interest in new drying techniques that lead to energy savings. Research in the literature concentrates on techniques such as steam/air impingement drying, condensing belt drying and impulse drying. Therefore, a cost assumption is not possible at this stage. The assumption is that a 20% emissions reduction is possible (Chan, 2019).

Figure 19: Pulp & paper industry – Technology letter: New drying techniques

Elysis process (Inert / Non-carbon anode)

Possible Availability
- 2024 (Elysis process)

Emission reduction potential
- 100% of process emissions

State of development
- Inert anodes (TRL 5)
- Elysis process (TRL 6)

Costs
- –

Technology description

The conventional Hall-Héroult process uses carbon anodes, which lead to process emissions during the reaction. The use of inert anodes makes it possible to avoid these emissions. Instead of CO_2, oxygen is formed at the anode. In addition to the use of inert anodes, there is the possibility of wetting the anodes, which leads to improved contact between the anode and molten aluminium. Both adjustments are combined in the Elysis process. The Elysis process is considered the first climate-neutral process for the production of aluminium as long as climate-neutral electricity is used. The process leads to a significantly longer lifetime of the anode as well as lower operating costs by 15% and higher productivity of 15% (Chan, 2019).

Figure 22: Aluminum industry – Technology letter: Elysis process (inert/non-carbon anode)

Carbo-thermic reduction

Possible Availability
- 2050 or later

Emission reduction potential
- 100%

State of development
- Laboratory phase (TRL 2 - 3)

Costs
- Estimated investement costs: 3000 €/t Al

Technology description

The carbo-thermic reduction process is the only non-electrochemical aluminium production process with application potential. In the process alumina (Al_2O_3) reacts with carbon at high temperatures (> 2000°C) to form aluminium and CO. The process can have benefits in comparison to the Hall-Héroult process, such as the 20 – 30% reduction of energy per unit Al, a 50% reduction of capital costs and significantly lower operating costs (Chan, 2019).

Figure 21: Aluminum industry – Technology letter: Carbo-thermic reduction

Advanced Mineral Recovery Treatment

Possible Availability
- –

Emission reduction potential
- Elimination of red mud as hazardous waste

State of development
- Pilot plant (TRL 3 - 4)

Costs
- –

Technology description

This process has a small impact on overall efficiency, but is important with respect to the environmental impact of aluminium production. During the production of alumina (Al_2O_3) from Bauxite, large quantities of hazardous solid waste (red mud) are created. Within the Advanced Mineral Recovery Technology (AMRT), red mud can be smelted without any pre-treatment, producing crude iron and viscous slag suitable for industrial mineral wool. The technology thus manages to convert a product, hazardous for the environment into two co-products, thus preventing a possible hazard to the environment from red mud. Within the Bayer process, the technology leads to an increase in exergy efficiency from 3 - 4 to 9 - 13% (Chan, 2019).

Figure 20: Aluminum industry – Technology letter: Advanced mineral recovery treatment

Power-to-Heat for steam

Possible Availability

- 2020 (Electric boiler)
- 2025 (Heat pumps)

Emission reduction potential

- 100%

State of development

- Heat pump (100 – 150 °C) (TRL 7 – 8)
- Heat pump (150 – 200 °C) (TRL 6 – 7)
- Electric boiler (TRL 9)

CO_2 abatement costs

- 2030: -54 – 40 €/t CO_2
- 2050: 76 – 131 €/t CO_2

Technology description

A large number of industrial processes require heat as energy source. In some cases, the heat level differs considerably. Temperatures from 100 to over 1000°C are reached. For this reason, different power-to-heat processes are used for decarbonisation. In the low-temperature range (up to 200°C), the deployment with high-temperature heat pumps is possible (Agora Energiewende, 2021). The expectation for the use of high-temperature heat pumps on an industrial scale is 2025 at the earliest, assuming optimum technology development (Krook-Riekola, 2022).

Electrode boilers reach temperatures of up to 500°C. These are already market-ready and available, and lead to a complete reduction in emissions when climate-neutral electricity is used (Krook-Riekola, 2022; Mobarakeh, 2022). Within Agora Energiewende (2021), abatement costs for 2050 are given as 76 - 131 €/t CO_2. This results in specific additional costs of 49 - 83% compared to conventional processes (CHP or gas boiler) (Agora Energiewende, 2021).

Figure 23: Cross-sectoral technologies – Technology letter: Power-to-heat for steam

4. Policy Recommendat Conclusions

The overview of the technologies needed to decarbonis [...] potential availability are barriers. Therefore, this concl [...] overcome these barriers. In addition, an assessment is [...] feasibility of implementation in China.

Market-based instruments

CO_2 pricing

Within the context of a market-based ecological transformation, carbon pricing is a key element. CO_2 pricing is the most effective measure for transformation because, at present, it leads to higher costs for conventional technology compared to carbon-neutral technology, providing an incentive to replace the conventional technology. However, carbon pricing is not sufficient in itself. In the short to medium term, a low CO_2 price means that other instruments in line with the CO_2 price are needed to enable capital-intensive investments in new technologies. Over time, the carbon price will increase and replace currently necessary subsidies. In industry, a minimum CO_2 price may be an option, as it would provide companies with a clear price signal (Agora Energiewende, 2021). This has the advantage of providing development certainty for long-term investments (dena, 2021).

Green lead markets

The introduction of green lead markets is particularly recommended in the steel industry (direct reduction of iron with hydrogen – H_2 – DRI), the cement industry (CCU/S) and the production of chemical raw materials (chemical recycling and methanol to olefins/aromatics – MTO/MTA). These sectors require high investments as well as an increase in operating costs in some parts when switching to climate-neutral production methods. Green lead markets can create a secure sales market, reducing investment risk (BDI, 2021). To implement green lead markets, the government can either set quotas for certain

Current renewable energy subsidies in Germany

In Germany, the promotion of renewable energies has focused, in particular, on the price of electricity. The expansion of photovoltaic, wind and biomass power plants has been promoted via the EEG apportionment. The EEG apportionment has been allocated exclusively to the price of electricity. This approach results in higher abatement costs for the power sector and reduces the financial burden for other sectors that are also part of the transformation.

For this reason, the German government abolished the EEG apportionment in 2022. Currently, renewable energies are promoted by setting expansion targets and tenders for subsidies. The setting of expansion targets has a control function (EEG).

Principle of green lead markets

In green lead markets, manufacturers are obliged to create a certain proportion of their products with climate-neutral materials (production without emitting CO_2). This obligation guarantees companies in the basic materials industry a secure sales market for the production of green (climate-neutral) materials. There is no risk of carbon leakage when implementing green lead markets, as goods exported abroad are not affected. Furthermore, the requirements also apply to foreign companies, which can thus also be incentivised to change their production to green materials (BDI, 2021).

products or specify a mandatory share in government procurement measures. A CO_2 shadow price[10] has been applied to procurement transactions at the state level in Germany since 2022. This takes into account the CO_2 emissions of a product over its entire life cycle and leads to potentially higher procurement costs in contrast to sustainable products.

In the case of quotas, it is possible to pass on the additional costs incurred by manufacturers to the end customer. In general, the advantage of setting quotas is the specific promotion of certain products, such as "green" steel or cement. This is not necessarily the case with public procurement, as it depends on the projects put out to

[10] Definition of "CO_2 shadow price": The CO_2 shadow price is a fictitious price for CO_2 emissions intended to represent the potential damage caused by the CO_2 emissions of a product. In contrast to the CO_2 price, the CO_2 shadow price does not have to be paid, but it has to be taken into account in decision-making.

tender. However, the advantage of this route is that implementation can be relatively direct, as the decision is made solely by the government (BDI, 2021).

Carbon contracts for difference (CCfDs)

The use of CCfDs is particularly advantageous in the steel, cement and chemical industries, where the transformation requires early investment in new, expensive technologies (e.g. H_2 – DRI).

CCfDs can be distinguished into two groups: energy carrier and product CCfDs. Energy carrier CCfDs compensate, for example, the price difference between 1 MWh of gas (+ most effective CO_2 impact) and 1 MWh of green hydrogen. On the other hand, product CCfDs cover the differential cost of producing 1 tonne of steel via the blast furnace route and 1 tonne of steel via the H_2-DRI route (BDI, 2021). This includes plant-specific costs.

Carbon contracts for difference (CCfDs)

CCfDs are used to finance key technologies whose CO_2 reduction costs are significantly higher than current and future carbon prices. CCfDs compensate for the additional costs incurred compared to a conventional technology. The contract is between the public sector and individual suppliers. There is a link between CCfDs and the evolution of the CO_2 price. The public sector covers the additional costs until the CO_2 price exceeds the CO_2 reduction costs (strike price). If the CO_2 price exceeds the strike price, repayments are required (dena, 2021).

Initially, the use of product CCfDs is recommended due to the coverage of plant-specific costs. Planning security is guaranteed by covering the costs for as long as possible. For the possible use of CCfDs, there must be a legal framework that defines the eligible technologies.

Implementation of low-carbon technologies

Achieving climate neutrality in industry depends particularly on the expansion of renewable energies. Without climate-neutral electricity, it is impossible to achieve climate neutrality in industry. On the one hand, this is due to the electricity-intensive processes and on the other hand, renewable electricity is required to produce green hydrogen (dena, 2021).

In this respect, industry can actively influence the further implementation of low-carbon technologies. One possibility is to conclude Power Purchase Agreements (PPA), in which the company and energy supplier enter into a contract for the supply of renewable energy. These agreements have the advantage of excluding the investment costs for the company while allowing for a competitively priced supply of electricity. Furthermore, the conclusion of PPAs ensures the long-term supply of renewable electricity.

Other necessary measures need to be taken on the policy side. The expansion of renewable energies requires sufficient land. Policymakers should use spatial planning to make areas available for renewable energies. Furthermore, it is necessary to accelerate and simplify approval procedures for renewable energies in Germany in order to accelerate the transformation. When considering the promotion of renewable energies in the overall context of the energy system, further measures are needed in other areas.

Due to increasing fluctuations in the power grid, flexible technologies are needed to ensure the supply of electricity at optimal costs. Therefore, the design of the promotion of combined heat and power (CHP) plants should ensure that they serve grid stability (dena, 2021). Furthermore, it is important to avoid possible path dependencies. One option is to link funding to the requirement of H_2 readiness (retrofitting for hydrogen is possible) in order to ensure that these technologies can be converted to efficient and climate-neutral operations in the future. As in the previous explanation, hydrogen is an essential component of the transformation. A ramp-up of the hydrogen economy is necessary for the industrial use of hydrogen. On the one hand, such a ramp-up requires a regulatory framework that integrates hydrogen into the current energy system and defines which requirements apply to the use of hydrogen (CO_2 footprint, purity, etc.) (dena, 2021). On the other hand, it is necessary to create a hydrogen market and planning security for companies. To achieve this, subsidies for certain cost-intensive technologies are necessary.

Improving energy efficiency

Improving energy efficiency reduces energy consumption and decreases costs, which reduces the speed needed for other transformation steps (low-carbon technologies). For products, energy efficiency can be promoted through the push & pull principle. In this process, the law sets minimum standards for products. If products do not meet the minimum standards, they are banned from the market (European Economic Area for the EU regulatory framework). At the same time, particularly efficient products are promoted, for example, by encouraging their replacement before the end of their life cycle. Furthermore, labels highlight particularly efficient products in order to inform end consumers. The disadvantage of the push & pull principle is that the process of establishing minimum requirements is time consuming and cost intensive (BDI, 2021).

In Germany, the efficiency potential is greatest in the building sector. This also applies to industrial buildings and is not exclusively limited to households. The efficiency of buildings can be improved through renovation/refurbishment or by improving the technical building equipment. In order to promote renovation, subsidies should be linked to the level of renovation, with a higher level of renovation leading to higher subsidies. Furthermore, renovation should follow the 'worst first' principle, as the savings potential is the highest (dena, 2021).

Lastly, it is necessary to take an in-depth look at industry. When integrating new systems, a commitment should be made to using the most efficient technologies. Systems that are incompatible with the climate neutrality target should no longer be subsidised. Industry should benefit from shorter depreciation periods for investments in energy efficiency measures in order to achieve shorter amortisation periods (dena, 2021).

In addition, the role of industry in the flexibilisation of electricity demand needs to be considered. Demand adjustments (DSM) can accommodate fluctuations in electricity generation from wind and photovoltaic power sources. This has cost benefits, as electricity prices decline significantly during peak load periods due to oversupply. Therefore, the use of demand-side management should be encouraged (Agora Industrie & Future Camp, 2022).

There is a general need to examine the compatibility and necessity of existing tax exemptions from energy and carbon prices.

Implementing the measures identified in Chapter 3 (energy management system, energy audits) should be mandatory to push and support companies to continuously improve their energy efficiency, linked with financial support. This measure would help to reduce energy demand and accelerate the overall reduction of emissions.

Using waste heat

The use of waste heat is also an efficiency measure. Waste heat can be used in industrial plants or in local and district heating networks.

The use of waste heat at low temperatures (< 100°C) in local and district heating networks is of particular merit. This could allow the use of waste heat sources such as server rooms, as well as the use of wastewater, lakes or rivers, as heat input for heat pumps. This requires the conversion of local and district heating grids (e.g. temperature reduction, flexibilisation, etc.), which is summarised under the term District Heating Networks 4.0. As this is an infrastructure project, it is necessary to take a systemic approach that considers both district heating networks and buildings. Therefore, it is recommended that municipalities be required to create municipal heating plans, as this allows for a holistic view (BDI, 2021).

Promoting the use of waste heat should include the promotion of inter-company use. Companies should be integrated into waste heat networks and encouraged to develop a waste heat utilisation strategy with other companies in the surrounding area (Agora Energiewende, 2021; dena, 2021). Possible incentives include the funding of inter-company concepts and government guarantees for implementing complex projects in which many stakeholders are involved. Finally, creating a waste heat atlas[11] can help identify waste heat potentials and enable concrete local concepts (dena, 2021).

Striving for a circular economy

The previous concepts have mainly focused on how a more efficient and climate-neutral use of energy can be achieved. In a circular economy, the focus is on closing material flows and reducing the use of materials. This aims to limit the use of primary materials and can significantly reduce costs, energy requirements and CO_2 emissions.

The recommendations presented below are divided into quotas, bans, standards and taxes.

In the EU, bans on the use of single-use plastic and, in part, on the export of plastic waste have already been introduced. In future, the ban on all plastic waste for export should be extended. Furthermore, the inclusion of other easily substitutable products should follow (BDI, 2021).

Quotas for the use of recycled materials can promote the shift to a circular economy. This requires companies to use a certain proportion of recyclates in their products. A steady increase in quotas gives companies a clear signal

[11] Definition of waste heat atlas: A waste heat atlas provides information on the location and volume of waste heat sources in a given area (industrial plant, town, country).

about how production will change in the future. This provides long-term information on necessary investments. When setting quotas, the entire life cycle and energy efficiency must be taken into account (Agora Energiewende, 2021). Providing information on the intended effect at an early stage can simplify the introduction. The use of recycled materials is crucial, as the replacement of primary materials is necessary, albeit not guaranteed by recycling quotas (downcycling).

Quotas for recyclates are specified at the recycling level. In order to be able to reuse products, it is necessary to introduce product design standards. In these standards, manufacturers are legally required to design their products in a way that facilitates their reuse (repair) or recycling. This includes product-specific regulations such as the standardisation of product components, disassembly-friendly product design, restriction of composite materials, restriction of small-part waste, and others (BDI, 2021). Another possibility is to establish specifications for the repair and durability of products. Firstly, minimum standards should be raised and legal requirements introduced for the recyclability of all non-renewable materials. In addition, barriers to the use of secondary materials should be removed by reviewing existing standards and norms. Finally, regulatory requirements can include the use of deposit systems and specific requirements for the end-of-life phase.

As a final instrument, it is recommended to implement taxes on the import and production of primary materials. These should include materials for which the use of secondary materials is already possible (e.g. certain plastic products). The tax can then lead to higher recycling rates, waste prevention and reduced use of primary materials while strengthening the market for secondary materials (dena, 2021). Furthermore, a landfill tax could lead to a reduction in the use of non-recyclable materials and waste.

Conclusion

The extent to which the recommendations presented are transferable to China depends on the current economic and political conditions. Instruments such as carbon pricing, green lead markets, CCfDs, quotas, subsidies and bans can already be adapted to the situation in China.

Specific measures concerning the development of renewable energies require further consideration for China. The availability of land and the necessary future demand for China would have to be determined in order to enable a qualitative assessment.

The most important difference, however, is the different macroeconomic situation. Germany has been growing modestly for years (about 1–2% GDP growth per year) while gradually reducing energy demand and CO_2 emissions. China's rapid economic growth has so far been accompanied by significant growth in production quantities.

In the industrial sector, the difference in the remaining technical lifetime of installations is significant. Over the next ten years, Germany will experience a reinvestment cycle in which up to 50% of the installations in specific industrial sectors will have to be replaced. In China, the average age of installations tends to be around 15 years, which means that the equivalent timeframe takes us to the 2030s–2040s.

In Germany, the use of instruments in addition to CO_2 pricing is recommended, as new non-commercial technologies with high initial investment costs are needed. If the necessary transformation in China takes place in the reinvestment cycle, the investment and operating costs of these technologies may have already considerably decreased thanks to technological progress and economy-of-scale effects. Therefore, it is probably less important to implement instruments in addition to CO_2 pricing.

In the context of the transformation to a climate-neutral energy system, China has yet to face challenges that Germany has already confronted.

The upcoming coal phase-out and the fundamental transformation of industry in China may lead to socio-economic challenges in the affected regions. Therefore, it is recommended to provide structural change support for these developments and to involve different stakeholders in order to minimise possible social issues.

In summary, both German and Chinese industry are facing economic and technological challenges in order to achieve the political climate protection targets. In particular, the rapid integration of new technologies has a decisive impact. In the short term, this can only be achieved with the help of additional economic instruments, such as CCfDs and green lead markets. Positive developments can facilitate the desired conversion of Chinese industry, as expansion leads to cost-reduction effects.

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