Pathways to a near carbon-neutral German industry sector by 2045: A model-based scenario comparison and recommendations for action

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Abstract

In 2018, emissions from the industrial sector in Germany amounted to around 190 million tons of CO_2 equivalents, the majority of which were caused by companies in energy-intensive industries. According to Germany's reduction target for this sector, these emissions must fall to 118 million metric tons by 2030. Its high dependence on fossil fuels, technical restrictions and hardly avoidable process emissions pose major challenges for the sector. In order to achieve near climate-neutrality in 2045, these challenges require a profound transformation in the basic materials industries. This contribution presents the results of a comprehensive bottom-up assessment comparing four technology pathways to a near carbon-neutral German industry sector until 2045. The analysis was carried out using the bottom-up energy demand model FORECAST, which is characterized by a high degree of technology and process detail. Its results show that the goal of a nearly carbon-neutral industrial sector in 2045 is possible, but will require enormous efforts. Large amounts of CO_2-neutral secondary energy carriers like electricity and hydrogen will be needed in addition to improvements in material and energy efficiency. Depending on the technology focus, the amount of electricity used nearly doubles from 226 TWh up to 413 TWh in 2045. In the case of a "hydrogen economy," the industrial use of hydrogen as a feedstock and as an energy source increases up to 342 TWh in 2045. The time horizon to 2030 is crucial if the transition to a near climate-neutral industry sector is to succeed by 2045. It must be possible to scale up CO_2-neutral processes from the pilot and demonstration stage to industrial level by 2030 and enable their economic operation. This contribution therefore also places particular emphasis on the period up to 2030 and discusses those options for action in this time frame which have proved to be robust in several scenarios. The need for additional action is also elaborated based on the scenario results.

Introduction

With approximately 190 $MtCO_2$-eq. (million tons CO_2 equivalent in 2018), the industrial sector was responsible for about 23 % of GHG (greenhouse gas) emissions in Germany in 2018 (Herbst et al. 2021). The majority of these emissions stem from energy-intensive industries (e.g. metal production, basic chemicals, non-metallic minerals), which at the same time are responsible for about 70 % of industrial energy demand (AGEB 2020). Differentiated by end-use, most industrial GHG emissions are associated with high-temperature process heat, either in the form of steam or hot water or from the direct firing of different types of furnaces. The high temperatures and specific requirements of industrial furnaces limit the use of renewable energy to biomass or secondary energy sources. Process-related emissions also account for a significant share of industrial emissions. They stem from chemical reactions within the production process and their mitigation is technically difficult or even impossible with the processes currently in use (Herbst et al. 2021, Herbst et al. 2018).

There is political and social consensus in Germany concerning the goal of long-term GHG neutrality, but the sector-specific technology pathways as well as the policy frameworks

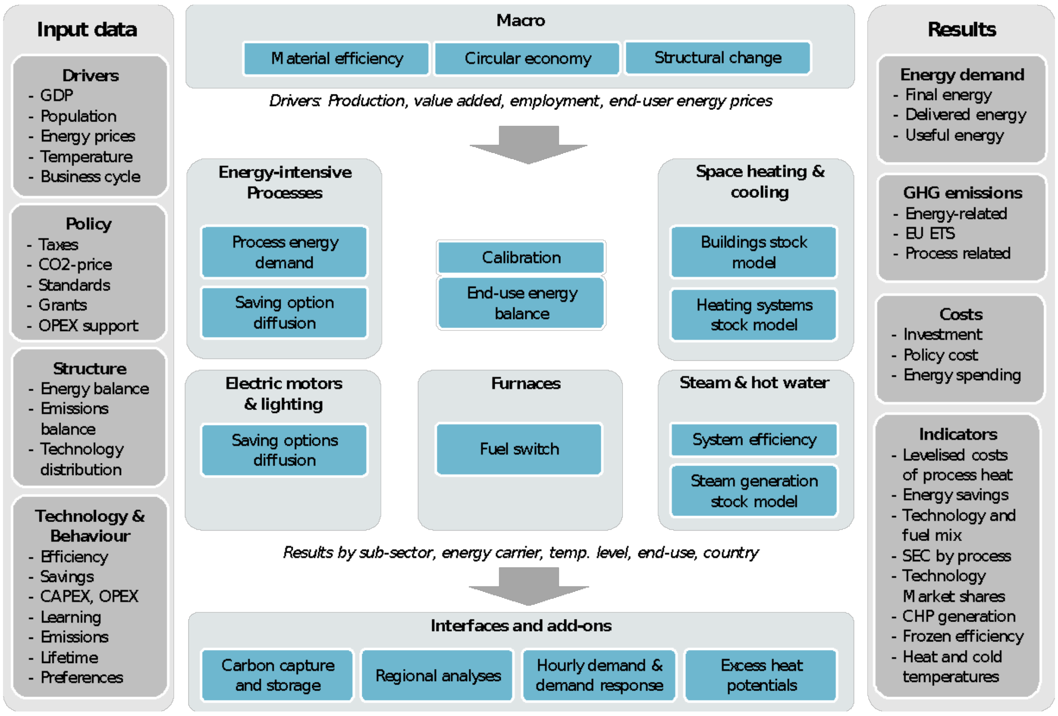


Figure 1. FORECAST model structure for the industrial sector. Source: Fleiter et al. 2018.

and instruments to achieve this are still under discussion (SPD, Bündnis90/Die Grünen und FDP 2021). There are many different decarbonisation strategies for industry, e.g. electrification of process heat, switching to hydrogen or "green" gas, increased use of biomass, market introduction of low-carbon processes, use of carbon capture and storage (CCS) combined with the use of CO_2 (CCU), expanding the circular economy and a more efficient use of materials. However, the individual contributions of these measures and their efficiency are still debated (Luderer et al. 2021, Prognos et al. 2021, BCG 2021, Fleiter et al. 2021, dena 2021). In particular, new technologies differ in their maturity and distance from market, as well as in their dependence on resources and infrastructure. The year 2030 represents an important milestone on the road to long-term CO_2 neutrality, for which Germany has set a reduction target of 118 Mt = ~57 % compared to 1990 for the industrial sector (German Federal Climate Change Act 2019). At the present time, however, the currently adopted and implemented instruments are not sufficient to achieve this target.

This contribution[1] presents the results of a comprehensive bottom-up assessment comparing four technology-pathways to a near carbon-neutral German industry sector until 2045 with particular emphasis on the period up to 2030 in order to discuss options for action in this time frame which have proved to be robust in several scenarios.

1. The content of this contribution has already been published in a German language project report (Herbst et al. 2021).

Methodology and Scenario Definition

METHODOLOGY

The following scenario calculations were conducted using the industrial demand model FORECAST (for a detailed methodology description see Fleiter et al. 2018). FORECAST is a bottom-up energy demand model that maps the technology structure of industry and models industrial energy consumption, emissions and costs at the process level. The model is hierarchically structured and divides industry into individual economic sectors or subsectors based on the German energy balance, to which specific industrial processes are assigned (consideration of more than 70 process technologies). Furthermore, technology areas such as electric motors, industrial furnaces, space heating and steam generation are modelled separately (see Figure 1).

All the major decarbonisation strategies can be considered in the scenario analysis (Fleiter et al. 2018, Herbst et al. 2021):

- **Incremental energy efficiency improvements** via best available technology (BAT) of existing plants: High resolution for processes and a comprehensive database of technological saving options enable the most accurate assessment of the existing efficiency potential.
- **Process switch** to new low-carbon or carbon-neutral production processes: High resolution of production routes and processes allows specific assumptions about the change to new production processes per production route. New processes may also be associated with a switch to a different energy carrier (e.g. hydrogen or electricity).
- **Fuel switch:** A stock model of steam generators including discrete choice modelling of the investment decision allows

the endogenous simulation of the fuel switch according to the economic efficiency and technology stock of the different steam generators. A simplified discrete choice approach is used when modelling fuel switching in industrial furnaces (Rehfeldt et al. 2018). Here, switching to biomass, electricity (electric boilers, heat pumps), hydrogen or PtG (power-to-gas) is possible.

- **CO_2 capture and storage (CCS) and utilisation (CCU)**: High process resolution allows the allocation of CCS to selected processes.
- **Recycling and material efficiency** along the value chain: Due to the large number of products considered and the separate modelling of primary and secondary routes of production, it is possible to make specific assumptions about advances in material efficiency and the circular economy.

The FORECAST model allows the simulation of policy impacts. These include price-based policies like subsidies or taxes, market-based instruments like the EU's Emissions Trading Scheme, but also standards like minimum energy performance standards for individual products. In a more aggregated form, policy instruments such as energy management or audits schemes are also considered by adjusting behaviour parameters. The need to simulate the impact of policies also requires the detailed representation of investment decisions in the model, because these are the main anchor for policy intervention. They include investments in new steam generation technology, energy efficiency improvements in existing installations, new electric motors, but also investments in radically new production plants. Investment decisions in energy efficiency are modelled based on the real-life behaviour of companies, which often deviates from cost-optimal decisions made assuming perfect knowledge, and faces manifold barriers (Fleiter et al. 2011). Real-life investment decisions are myopic (based on the costs and prices in a specific year) and simplified decision rules are applied (such as the payback time threshold) (Fleiter et al 2018). However, the scenarios discussed below are primarily used to illustrate possible technology paths to achieve climate neutrality in 2045 and do not analyse the effects of the individual policy measures needed to achieve them (for a detailed analysis of current policy instruments see Repenning et al. 2021).

SCENARIO DEFINITION

In the following, **four scenarios** are considered for the German industrial sector with a time horizon until 2045, which all aim at a GHG reduction of at least 95 % by 2045 compared to 1990. The scenarios differ in their technological orientation - this means that they reflect different, sometimes extreme, technological paths towards climate neutrality.

In the ***Electrification*** scenario, direct electric solutions in industry are preferred in all sectors, taking into account technology availability and feasibility (see Herbst et al. 2021). Hydrogen is used as a feedstock. In the ***Hydrogen*** scenario, hydrogen is assumed to be available in sufficient quantities and is used extensively, both as energy and a feedstock. The ***E-Fuels*** scenario assumes the availability of synthetic methane from 2030 onwards and that this is introduced into the natural gas grid in increasing proportions to completely replace fossil natural gas by 2045 (see Luderer et al. 2021). In addition to the three technology-focus scenarios, a technology ***Mix*** scenario is analysed without a specific technology focus. In this scenario, preference is given to solutions with high technology readiness levels (TRL) that are discussed in the scientific and public discourse as particularly promising and feasible.

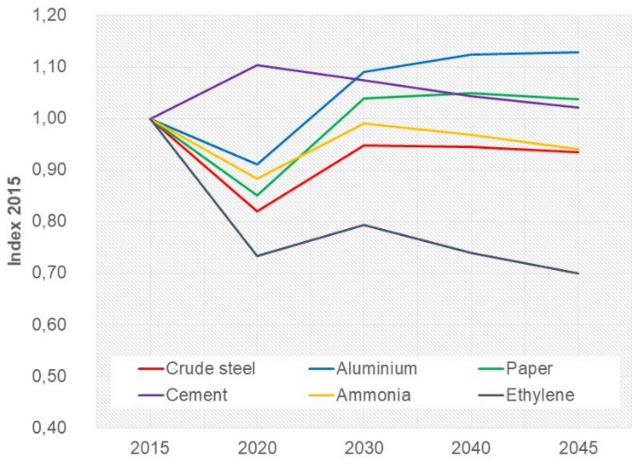


Figure 2. Production development of selected energy-intensive basic materials. Source: Herbst et al. 2021.

The **macroeconomic framework data** for the analysis of industry (gross domestic product, industrial value added, wholesale energy carrier prices) were defined within the framework of the energy system modelling Copernicus-Project ARIADNE (Luderer et al. 2021). In all scenarios, the gross value added of the entire industrial sector in Germany grows by around 1 % p.a. until 2045, although higher growth takes place in the consumer and capital goods industries, while the basic industries grow at a below-average rate (<1 % p.a.). The derived production volumes of important energy-intensive products in the basic materials industries (e.g. steel, cement, ethylene, ammonia, see Figure 2) are also based on identical assumptions in all scenarios about increasing material and resource efficiency as well as the circular economy.

Due to the overall **system perspective** of the ARIADNE project, the use of biomass for the industrial sector was limited or largely avoided in the scenarios due to the competition with other sectors, e.g. transport (see Luderer et al. 2021). The use of additional biomass was only allowed in the *Mix* scenario. The use of CCU/S was also limited to applications for which there are currently no sufficiently developed alternatives, e.g. production of cement and lime.

Results

ALTERNATIVE PATHWAYS TO NEAR CARBON-NEUTRAL INDUSTRIAL PRODUCTION BY 2045

All the scenarios achieve a reduction in greenhouse gas emissions from industry by 96 to 97 % by 2045 compared to 1990 (see Figure 3 and Table 1). The development of energy-related emissions follows the energy consumption discussed in the following section and is dominated by industry's demand for natural gas until 2030. The use of CO_2-neutral process technologies (e.g. hydrogen-based steel, new types of cement), direct electrification as well as material efficiency and circular

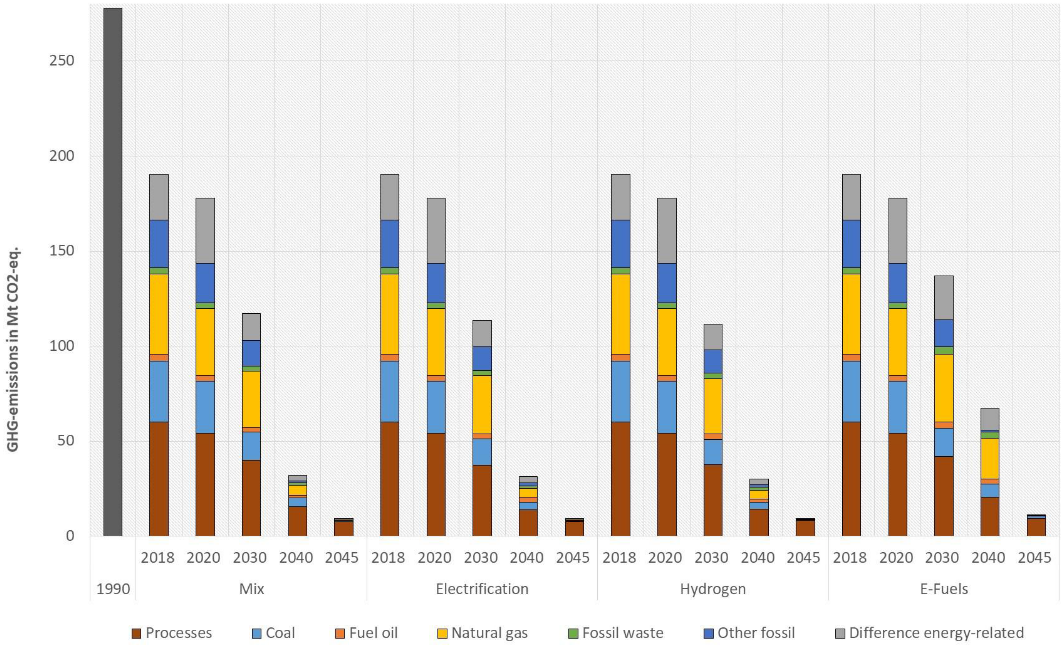


Figure 3. Industrial emissions by source [2018-2045, MtCO2-eq.]. Source: FORECAST Model – Fraunhofer ISI.

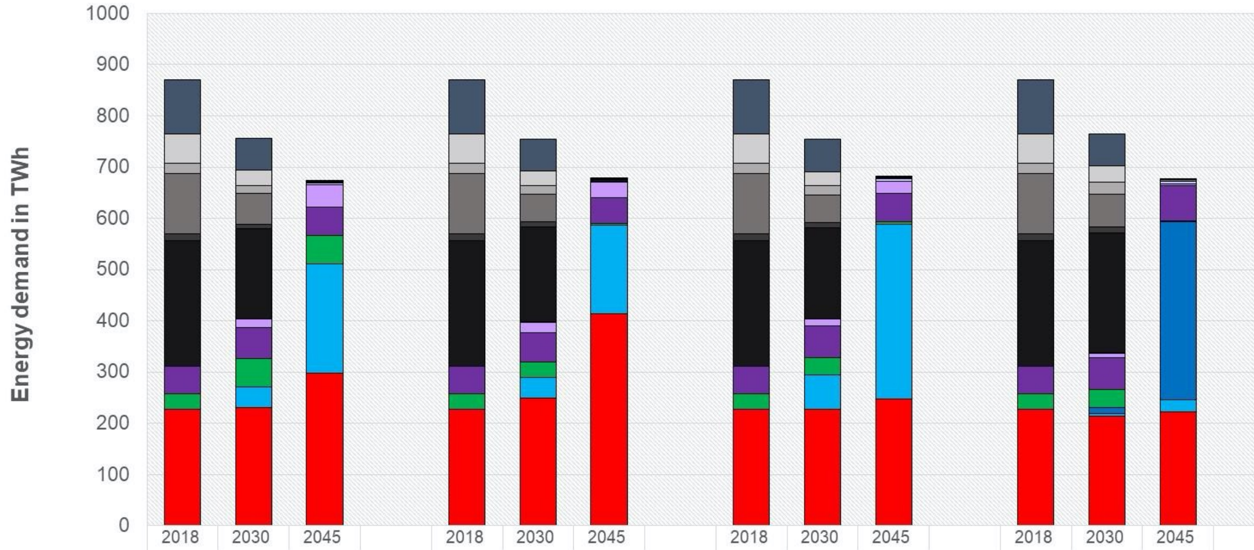
Table 1. Overview of near carbon-neutral industrial pathways. Source: Herbst et al. 2021.

Mitigation level	Year	Mix	Electrification	Hydrogen	E-Fuels
GHG mitigation in industry compared to 1990	2030	*-58%*	*-59%*	*-60%*	*-51%*
	2045	*-97%*	*-97%*	*-97%*	*-96%*
Mitigation option	**Sector**	**Mix**	**Electrification**	**Hydrogen**	**E-Fuels**
CCS	Steel, chemicals, cement and lime	*No*			*CCS for cement*
CCU	Cement and lime	*Cement and lime as CO_2 source*			*No*
Process switch to low-carbon production routes	Steel	*H2-DRI*		*PtG-DRI*	
	Cement	*Low carbon cement and clinker factor*	*Electric clinker and lime kilns*	*Low-carbon cement*	*Low-carbon cement*
	Chemicals	*MtO + H_2 methanol, H_2 electrolysis ammonia*		*MtO + PtG methanol, H_2 electrolysis ammonia*	
	Glass	*H_2 glass melting*	*Electric melting*	*H_2 glass melting*	*Glass melting (status quo)*
Fuel switch	Industrial furnaces	*H_2, electricity, waste*	*Electricity dominant*	*H_2-burner furnaces and steam*	*Gas dominant*
	Steam and hot water	*Mix*	*Electricity dominant*	*H_2-burner furnaces and steam*	*Gas dominant*

Note: CCS - Carbon capture and storage, CCU – Carbon capture and usage, MtO – Methanol to olefins, DRI - Direct reduced iron, PtG - Power-to-gas; H2 – Hydrogen.

economy measures result in a marked drop in energy-related emissions in the following decade until 2040. The remaining emissions of 9–11 $MtCO_2$eq. in 2045 are dominated by smaller distributed process emissions (for example from the ceramics industry). In the *Mix*, *Electrification* and *Hydrogen* scenarios, a GHG reduction of 58 to 60 % compared to 1990 is achieved by 2030. This means that the target for industry in 2030 according to the amended German Climate Protection Act of 118 Mt-CO_2eq., which corresponds to -57 %, is met or even slightly over-achieved. With a reduction of 51 % in 2030, the *E-Fuels* scenario does not achieve the new sectoral target for industry. This is due in particular to the remaining energy-related emissions in the system, as only a limited blending of synthetic methane into the natural gas grid can be assumed in the short to medium term (~5 % in 2030, see Luderer et al. 2021).

Figure 4 shows the German industrial energy demand for both final energy consumption and feedstock uses (in the basic chemical industry). A significant decrease in energy demand (~22 % compared to 2018) is observed in all scenarios. This decline is due to the fact that energy and material efficiency



	Mix			Electrification			Hydrogen			E-Fuels		
	2018	2030	2045	2018	2030	2045	2018	2030	2045	2018	2030	2045
Naphtha	105	63	0	105	63	0	105	63	0	105	63	0
Other fossil	57	30	0	57	28	0	57	28	0	57	32	0
Waste non-RES	21	15	0	21	17	0	21	18	0	21	23	0
Coal	118	60	1	118	54	1	118	54	1	118	63	4
Fuel oil	13	9	0	13	10	1	13	11	0	13	12	0
Natural gas	245	175	2	245	184	3	245	177	2	245	235	0
Solar energy	0	0	0	0	0	0	0	0	0	0	0	0
Other RES	0	0	3	0	0	1	0	0	5	0	0	5
Ambient Heat	0	16	44	0	20	31	0	13	23	0	8	4
District Heat	53	61	56	53	59	49	53	63	56	53	63	68
Biomass	32	56	54	32	30	4	32	34	4	32	35	3
Syn. methane	0	0	0	0	0	0	0	0	0	0	12	347
Hydrogen	0	41	214	0	40	173	0	66	342	0	4	23
Electricity	226	230	298	226	249	413	226	227	248	226	214	223

Figure 4. Industrial energy demand (energy and feedstock) by scenario and energy carrier [2018-2045, TWh]. Source: Herbst et al. 2021. Note: TWh – Terawatt hours, RES - Renewable energy sources, Syn – Synthetic.

measures as well as the increase in recycling-based processes more than compensate the growth from the assumed steady increase in industrial value added. Converting process heat and feedstock demand to CO_2-neutral secondary energy sources is a key strategy across all scenarios (see Table 1), without which a CO_2-neutral industrial sector is not possible. Depending on the selected technology focus of the scenarios, there are clear differences in the importance of electricity, hydrogen and synthetic methane (PtG) (see Figure 4).

In the *Mix* scenario, electricity is the dominant energy carrier in 2045 with 298 TWh, followed by hydrogen with 214 TWh. In this scenario, hydrogen is used where direct electrification is not possible (e.g. as a feedstock for basic chemicals) or because electrical processes are not yet technically advanced enough (e.g. steel industry). Otherwise, there is only a limited use of hydrogen in the high-temperature range of industrial process heat (for example in the glass industry, see Table 1). The energy mix is more diverse in other industrial furnaces, steam generation and low-temperature heat (<150 °C). Biomass continues to be used by industry in this scenario, but consumption increases only slightly (~54 TWh, compared to 32 TWh in 2018).

In the *Electrification* scenario, electricity consumption almost doubles compared to today's figures, from 226 TWh in 2018 to 413 TWh in 2045. This is mainly due to the electrification of process heat across all sectors (see Table 1 and Figure 5). This applies to high-temperature as well as medium- and low-temperature processes, for example by using electric steam boilers or heat pumps. In this scenario, hydrogen demand increases to 173 TWh in 2045 and is used in the steel industry and as a feedstock for the basic chemical industry for the production of methanol (mainly as an intermediate for olefin production) and ammonia.

In the *Hydrogen* scenario, the strong increase in the consumption of (green) hydrogen completely replaces the use of fossil fuels such as natural gas, naphtha, coal and others by 2045 (see Figure 4). Hydrogen thus becomes the main energy carrier for providing process heat as well as being used as a raw material in the chemical industry. At 66 TWh, the demand for hydrogen in 2030 is significantly lower than the demand for fossil fuels, but still substantial. Due to the assumed rapid conversion of the industrial plant stock, there is a relatively strong increase in hydrogen demand, especially in the period from 2030 to 2040, to 342 TWh in 2045 (see Figure 6). In some cases, this requires early replacement of technologies before they reach their end-of-life. Electricity consumption in this scenario increases only slightly from 226 TWh today to 248 TWh in 2045, which means that electricity and hydrogen are the dominant energy carriers for industry in 2045.

The *E-Fuels* scenario is dominated by the demand for synthetic methane (347 TWh in 2045), which is prioritised across all end-use sectors. PtG is used as a feedstock for the production of steel, olefins and ammonia. In addition, gas continues to be an impor-

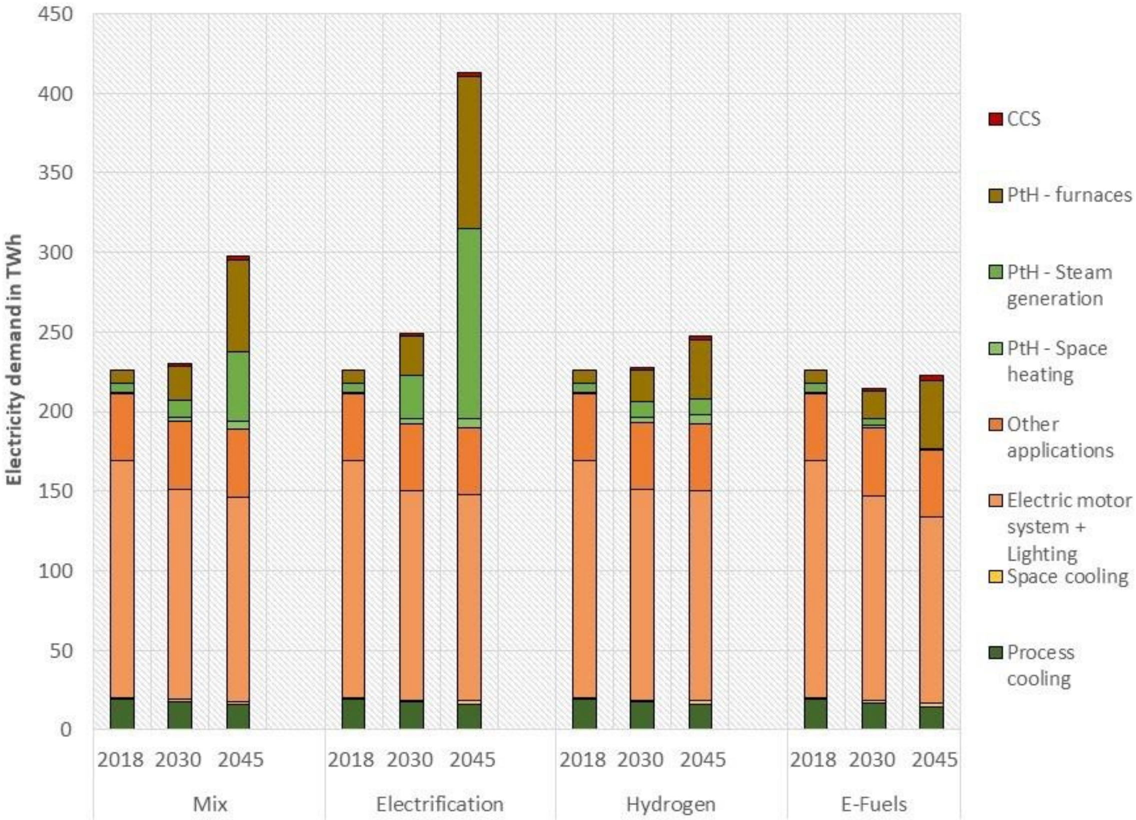


Figure 5. Electricity use by scenario and application [2018–2045, TWh]. Source: Herbst et al. 2021.

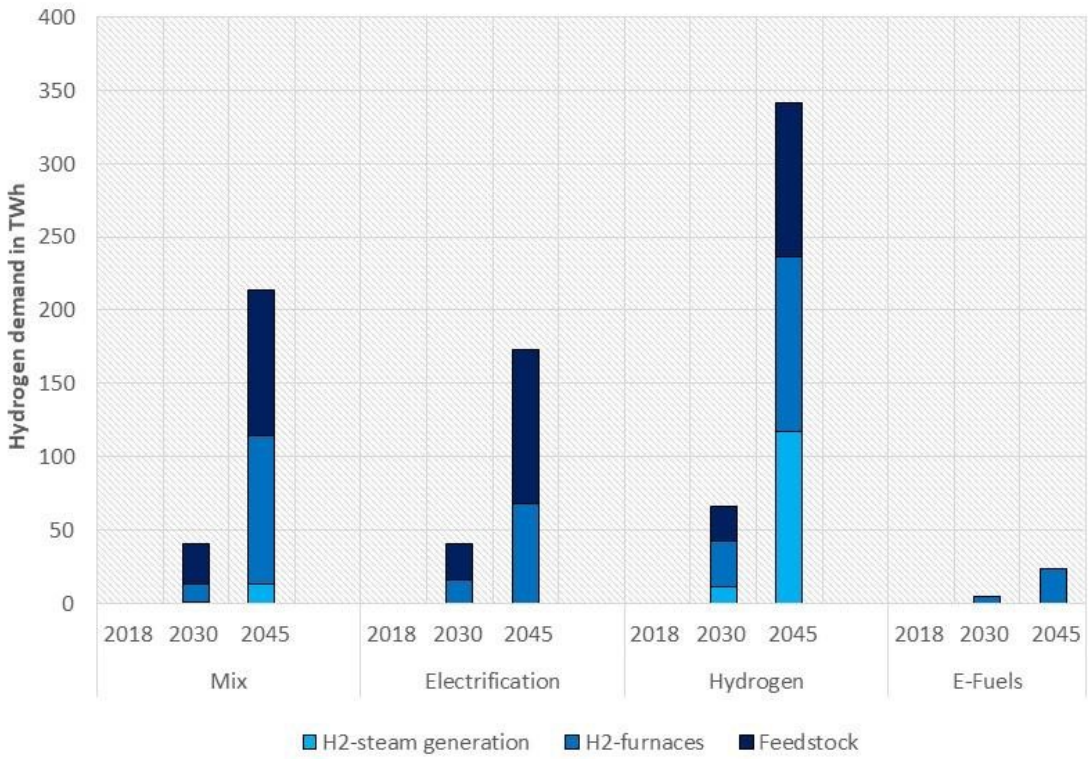


Figure 6. Hydrogen use by scenario and application [2018–2045, TWh]. Source: Herbst et al. 2021.

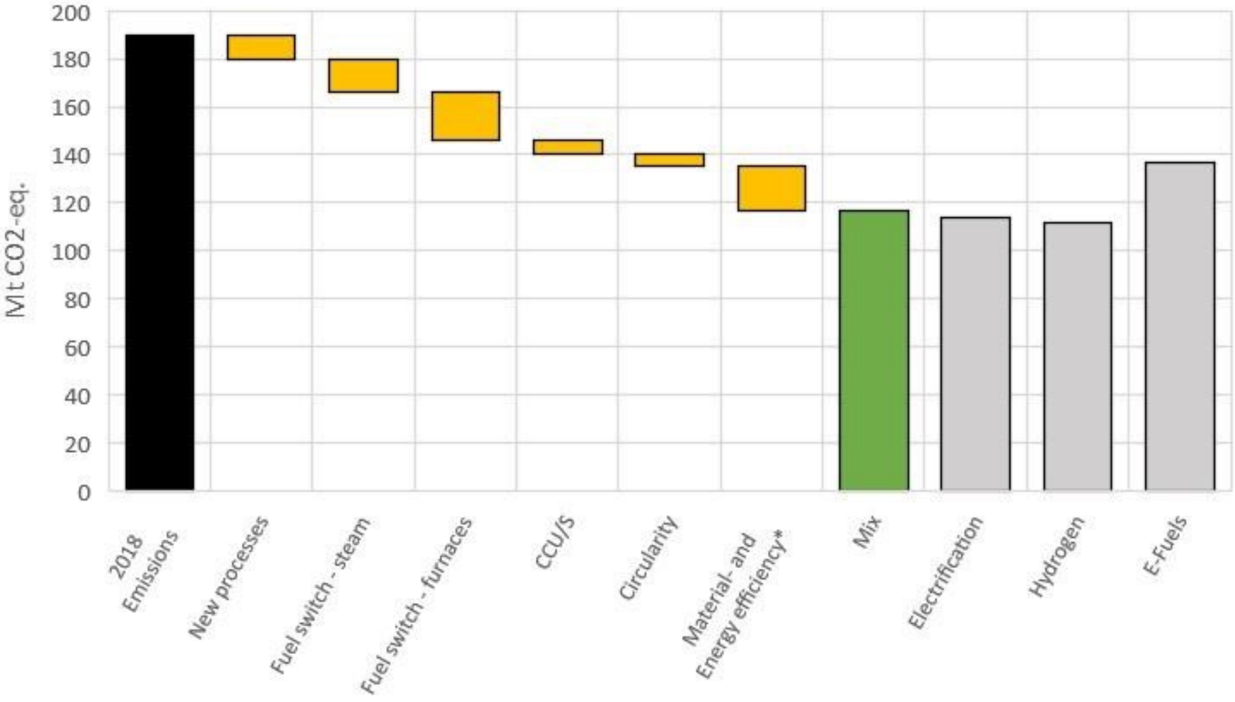


Figure 7. Contribution of individual abatement options to emission reductions by 2030 compared to 2018. Source: Herbst et al. 2021.

tant energy source for industrial furnaces and steam production. However, in 2030, the use of synthetic methane is only around 12 TWh, as only limited blending of synthetic methane into the natural gas grid can be assumed in the short to medium term.

In addition to the analysis of industry transformation presented here, other studies on this topic in Germany have also been published recently. Four of these studies are particularly relevant (Prognos et al. 2021, BCG 2021, Fleiter et al. 2021, dena 2021; for more details see Stiftung Klimaneutralität 2022). Comparing the *Mix* scenario with these studies reveals that all of them expect a medium- to long-term decline in final energy consumption in industry in the same range (~550 to 610 TWh in 2045) as this contribution (~570 TWh final energy demand excl. feedstock in 2045). Similar to the results shown above, electrification increases (~310 to 400 TWh in 2045) and hydrogen becomes more important (34 to 88 TWh excl. feedstock) in all the analysed studies. The greatest differences are found in the use of biomass for both energy and material use. These differences are due to the fact that this contribution assumed a limited amount of available biomass, which is given priority in other sectors, e.g. transport (see Luderer et al. 2021).

PRIORITIES UNTIL 2030

The period until 2030 is crucial if climate neutrality is to be achieved by 2045. In this period, CO_2-neutral processes must be scaled up from pilot and demonstration scale to industrial level and operated economically. Extensive investments in new plants are necessary and solutions must be implemented for the provision of CO_2-neutral hydrogen and electricity. To achieve this, the regulatory framework must be redesigned with the clear objective of climate neutrality. Furthermore, according to the new sectoral target, emissions from the industrial sector must fall from 190 $MtCO_2$eq. in 2018 to 118 $MtCO_2$eq. in 2030. This requires accelerated transformation of all sectors. In the following, options for action until 2030 are presented that have proven to be robust in several scenarios. Furthermore, the need for further action is elaborated based on the scenario results.

Based on the *Mix* scenario, Figure 7 shows the CO_2 reduction contributed by the individual fields of action or mitigation option by 2030 compared to 2018. Although the individual reduction contributions are to be classified as estimates, it is evident that all fields of action make an essential reduction contribution. The highest reduction of more than 30 $MtCO_2$eq. comes from fuel switching (steam and furnaces). This includes the switch to electricity, hydrogen and gas to generate process heat. Material and energy efficiency are estimated to contribute about 20 $MtCO_2$eq. These efficiency improvements additionally offset the emission increases due to economic growth and their gross mitigation effect would be even higher. Furthermore, it is also clear that the sectoral target in 2030 would not be achieved without the significant contribution of new processes and CCU/S, which together account for an emission reduction of about 15 $MtCO_2$eq.

Process switch to CO_2-neutral production routes

One central element of the transformation scenarios is the conversion of individual, particularly emission-intensive production processes in the basic materials industry to technologies that allow (near) carbon-neutral operation. These include the production of crude steel, cement clinker, olefins, ammonia and methanol. The scenarios assume that the first carbon-neutral plants will go into operation from 2025 onwards and that they will gain significant market shares as commercial plants by 2030. This corresponds to at least 5 Mt of crude steel production via hydrogen direct reduction (DRI) (equivalent to 20 % of primary steel production) in 2030, about 0.3 Mt (12 %) in ammonia production and 1.2 Mt (30 %) in olefin production.

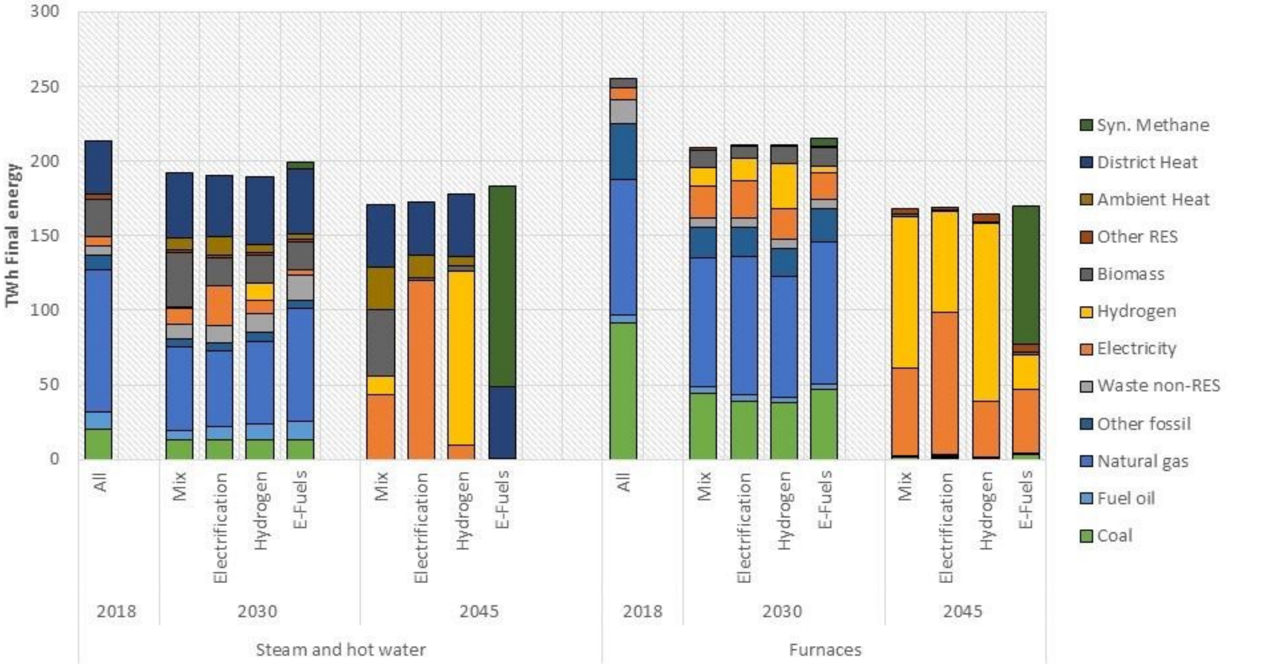


Figure 8. Contribution of individual abatement options to emission reductions by 2030 compared to 2018. Source: Herbst et al. 2021.

As olefin production switches to the methanol-to-olefins route, methanol production increases massively from 1.2 Mt (2018) to 5.5 Mt (2030) and 14 Mt by 2045. Converting primary steel production to the DRI process yields the highest CO_2 reductions, as CO_2-intensive coal is replaced.

This conversion is associated with investments - in many cases, new plants or extensive modernisation of the existing stock are necessary. The age structure of the existing stock accommodates this, as between 20% and 50% of the plants in important processes in the chemical industry (ammonia, methanol and olefins) and in primary steel production will reach the end of their calculated lifetime by 2030–2035 (Neuwirth and Fleiter 2020, Neuwirth et al. 2022). On the other hand, there is a risk of re-investment in fossil plants. In order to avoid this, windows of opportunity that arise from the existing modernisation cycles should be used for the conversion to CO_2-neutral production or prepared for this, for example, by means of direct reduction via natural gas.

In most cases, the conversion to CO_2-neutral processes also involves switching from cheaper fossil energy sources to more expensive CO_2-neutral secondary energy sources. A substantial build-up of the corresponding production capacities by 2030 is only possible if there is a reliable perspective for the economic operation of these plants.

Fuel switch for steam generation and industrial furnaces

In 2018, about two thirds of the CO_2 emissions from the industrial sector were related to the provision of process heat, which currently requires about 475 TWh of final energy – largely natural gas and coal. Supplying CO_2-neutral process heat is thus a key strategy for decarbonising industry. In the *Mix* scenario, switching to low-carbon energy sources is the most effective field of action here, with an estimated reduction of about 30 $MtCO_2$eq. by 2030 compared to 2018 (see Figure 7).

Process heat can be divided into furnaces for the respective production processes (255 TWh in 2018) on the one hand and steam generation (215 TWh in 2018) on the other. Figure 8 shows how energy consumption in these two segments will change by 2030 and 2045. While energy use in industrial furnaces in 2018 was still almost exclusively based on fossil fuels, electricity and hydrogen show a significant increase by 2030 in most scenarios, and displace coal in particular. This also includes large individual plants in iron and steel production, chemicals and the non-metallic minerals industry, which reduce their emissions primarily by switching to CO_2-neutral processes. The share of fossil fuels in steam generation also falls significantly from 143 TWh in 2018 to 90 TWh in 2030 in the *Mix* scenario. The use of natural gas decreases in all scenarios except *E-Fuels* and is substituted by electricity, hydrogen and biomass.

The plant stock for steam generation changes significantly in all scenarios except *the E-Fuels* scenario, which largely retains gas-based steam generation. The other scenarios show a decrease in natural gas-based steam generation of about 50 TWh by 2030, which is compensated by the use of high-temperature heat pumps, biomass, electric boilers and hydrogen.

The economic viability of CO_2-neutral steam generation depends mainly on the price difference between the energy carriers (see Figure 9), as investments only account for a small share of the total costs (Rehfeldt et al. 2021). Accordingly, multivalent steam generation, which combines existing combined heat and power (CHP) plants and natural gas steam boilers with new electric boilers, could be a key technology for starting the transformation of the plant stock in the next few years.

CO_2 capture, use and storage of process-related emissions (CCU/S)

About one third of industrial GHG emissions are process-related (2018: 61 $MtCO_2$eq.), which means they do not result from the use of energy sources (UNFCCC, 2021), but from chemi-

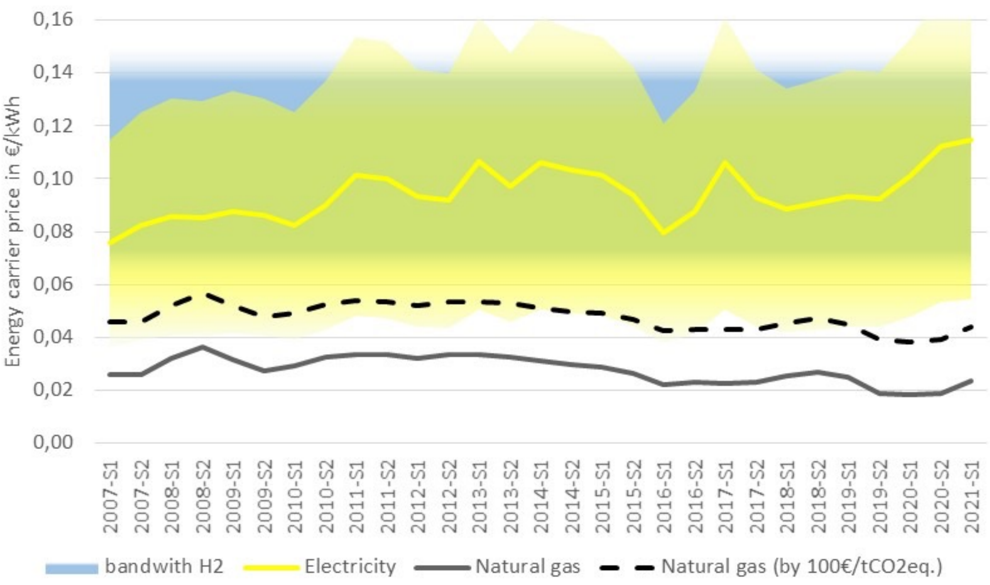


Figure 9. Energy carrier price spread 2007 to 2021 (electricity, natural gas, hydrogen). Source: Eurostat (2021), own calculations for hydrogen based on Luderer et al. 2021.

cal reactions within the production process. By 2030, these decrease to 40 $MtCO_2$eq. in the scenarios examined. Process changes in the steel and chemical industries and the reduced use of hydrofluorocarbons (HFCs) make the major contributions to this reduction. In cement and lime production, on the other hand, it is not sufficient to increase the use of additives or low-CO_2 binders and CO_2 capture and use or storage (CCU/S) is necessary in all scenarios.

By 2030, 30% of the production volume of cement and lime in the scenarios is equipped with CCU/S, thus avoiding 6 Mt of the then remaining CO_2 emissions. Until 2050, this is assumed to increase to 100 % of the production volume of cement and lime. Potential areas of application include basic chemicals, for example, as fossil carbon sources are no longer an option in a decarbonised system. For example, converting methanol and olefin production to the use of green hydrogen - as assumed in the *Mix*, *Electrification* and *H_2* scenarios - would require considerable amounts of carbon (for details, see Fleiter et al. 2021, Neuwirth and Fleiter 2020; one current example is the joint project of the BMWK “CO_2-Syn”/Power-to-Chemical 2022). This assumption is a very ambitious one considering the prerequisites involved, which include the required legal framework as well as the development of an infrastructure to transport carbon from the production plants to storage sites and consumers in the chemical industry. The socio-political consensus that CCU/S of process-related emissions is necessary for selected products from today’s perspective to achieve CO_2 neutrality by 2045 is another important factor.

Energy and material efficiency in combination with the circular economy

An ambitious increase in energy and material efficiency in all applications and sectors is a prerequisite for CO_2-neutral industrial production in the scenarios examined. This can reduce the final energy demand and thus lower the costs for expanding renewable energies, the grid and importing secondary energy sources. In the *Mix* scenario, final energy demand (excluding feedstock use) is reduced from 730 TWh (2018) to 637 TWh (2030) through increasing energy and material efficiency, while value creation increases at the same time. In this period, final energy intensity in relation to gross value added falls from 1.37 kWh/Euro in 2018 to 1.07 kWh/Euro in 2030, which corresponds to an average annual efficiency increase of about 2 %. By 2045, energy intensity decreases further to 0.83 kWh/Euro. For comparison, in real terms, energy intensity only decreased by an average of about 1.3 % annually between 2000 and 2015 (UNFCCC, 2021). Thus, by 2030, a significant increase in energy and material efficiency is necessary to stay on the scenario path.

A large part of industry’s electricity demand is accounted for by cross-cutting technologies such as motors, pumps, compressors and compressed air systems. In 2018, these technologies (including process cooling) accounted for 168 TWh of the total 226 TWh electricity used in industry. All scenarios assume an ambitious efficiency path for these applications, which reduces the electricity demand of these cross-cutting technologies to 150 TWh by 2030. This requires effective instruments to increase energy efficiency and overcome market barriers.

One example of the importance - but also the challenges - of an increased circular economy is secondary steel production, which is a key strategy in all scenarios. In the *Mix* scenario, the share of the secondary route from recycled steel scrap in crude steel production increases from 30 % (2018, 13 Mt) to 39 % (2030, 16 Mt). Without considering other effects, this increase saves 12.5 TWh of energy due to the lower energy intensity of the secondary route (blast furnace route: ~18 GJ/t crude steel, secondary route: ~3 GJ/t crude steel). As the blast furnace route predominantly uses coal-based energy sources, this corresponds to a GHG emission reduction of about 4 Mt. If this increment of the secondary route (~3 Mt) were produced via the primary process based on hydrogen (H2-DRI), an additional 8 TWh of hydrogen would be required annually. Increasing secondary route production is not a simple undertaking, however. Key challenges include the limited availability of steel scrap, the improvement of collection and sorting, and new product designs that enable the use of sorted scrap for high-value steel applications (Material Economics, 2018). These obstacles must be overcome to further increase the share of the secondary route to around 60 % by 2045.

Conclusions

The scenarios discussed show that the goal of a nearly climate-neutral industrial sector in 2045 is possible, but will require a great deal of effort. **Key challenges** include the **higher operational costs of CO_2-neutral technologies** (e.g. in the steel and chemical industry)**, infrastructure development, the effective implementation of CO_2 price signals along value chains, the reduction of uncertainties regarding large strategic investments as well as a clear perspective for the economic, large-scale industrial operation of CO_2-neutral processes** (Ueckerdt et al. 2021, BCG 2021, Fleiter et al. 2021, Neuwirth and Fleiter 2020). This means that this transformation towards nearly CO_2-neutral industrial production requires fundamental course-setting from policy makers, industry and society.

CO_2-neutral processes must be market-ready as early as 2025/2030 and have reached 100% stock diffusion by 2045. To achieve this, it must be guaranteed that these processes can be operated economically. This also applies to the decarbonisation of the remaining process heat applications (e.g. the use of bivalent/electric boilers in steam generation), the economic viability of which is largely dependent on the price difference between the energy sources (Rehfeldt et al. 2021).

All the scenario results are based on the assumption that CO_2-neutral secondary energy carriers such as electricity, hydrogen and PtG are available in large quantities and are used by industry. If hydrogen and PtG are produced in a CO_2-neutral way via electrolysis, there is a potentially very high demand for electricity, although this is outside the system boundary used by the industrial sector. One basic prerequisite for the industrial transformation described here is the **availability of sufficient green electricity as well as hydrogen or PtG**. In order to achieve the sectoral target of the Climate Protection Act, significant quantities of these energy carriers are already needed by 2030. These must be made available. At the same time, the significantly larger quantities that will be required in the period 2030–2045 should be taken into account when developing the infrastructure for transport and generation.

The conversion and expansion of the corresponding **infrastructures** to transport hydrogen and electricity must take place quickly and on a large scale. The development of a hydrogen network should take into account large industrial consumers of hydrogen. A **network** connecting the major industrial sites in a so-called **hydrogen backbone** seems to be a robust strategy that should be pursued in a targeted manner.

Energy and material efficiency as well as circular economy approaches must be ambitiously increased and their existing potential must be exploited using the best available and innovative technologies in order to reduce final energy demand and the costs of the transformation (infrastructure, renewables expansion, energy imports).

This must be accompanied by an **expansion of the regulatory framework** that goes well beyond the measures currently implemented and adopted.Repenning et al. 2021, for example, show that the measures implemented by the end of August 2020 are not sufficient to reach the emission reduction target of 118 million metric tons of CO_2 equivalents by 2030 in industry. Furthermore, Repenning et al. 2021 point out that the effects of changes in the CO_2 price are predominantly limited to the generation of steam to provide process heat in less energy-intensive areas of manufacturing (e.g. food, vehicle construction, other chemicals, rubber and plastics).

Consequently, even though a **strong CO_2 price signal from the EU ETS** is an important instrument to enable industrial transformation, other instruments will be needed in the short to medium term, as if the allowance price will not reach a level that is high enough to ensure that investments in new CO_2-neutral processes (e.g. for steel or basic chemicals) are economically viable, especially as these processes often use expensive secondary energy carriers such as electricity, hydrogen or PtG. The scenarios show how important it is to switch to new CO_2-neutral processes in order to achieve the emission reduction target. However, with abatement costs of 100–200 Euro/tCO_2, and an assumed CO_2 price increase to 125 Euros/tCO_2 in 2040 and to 250 euros/tCO_2 in 2045, it will not be possible to realize the investments in time without further subsidies and/or accompanying measures (e.g. carbon contracts for difference). Depending on the future prices of CO_2-neutral energy sources, the abatement costs could even be significantly higher (more than 200 Euros/tCO_2).

In addition, there are areas that are **not (effectively) addressed by the EU ETS** even assuming a higher CO_2 price, due to its design, but also various forms of market failure. These include, for example, changes along the value chains up to the end-use sectors. These areas have to be addressed by other elements of an instrument mix (e.g. green public procurement, quotas for CO_2-neutral materials, complementary recycling standards, border adjustment, product carbon footprints, regulations and others).

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