Key strategies to achieve deep decarbonisation of the industry sector – insights from a meta-analysis of recent climate neutrality scenarios for Germany

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Abstract

The EU aims to become the first climate neutral continent. To achieve this goal, the industry sector needs to reduce its GHG emissions to net zero or at least close to net zero. This is a particularly challenging task due to the high energy demand especially of primary materials production and the little potential to reduce this energy intensity when switching to other production processes based on electricity or hydrogen. In order to identify robust strategies for achieving a net-zero-compatible industry sector, the paper at hand analyses the transformation of the industry sector as described by a number of recent climate neutrality scenarios for Germany. Apart from overall industry, a focus is set on the sectors of steel, chemicals and cement. The analysed scenarios show very deep GHG emission reductions in industry and they appear to be techno-economically feasible by the mid of the century, without relying on offsets or on shifts from domestic production to imports. The scenarios agree on a suite of core strategies to achieve this, such as direct and indirect electrification, energy efficiency and recycling as well as new technological routes in steel making and cement. The scenarios differ, however, regarding the future mix of electricity, hydrogen and biomass and regarding the future relevance of domestic production of basic chemicals.

Introduction

For about a decade, the 2050 climate target of both the European Union (EU) and Germany was to reduce greenhouse gas emissions by 80 to 95 % relative to 1990. However, in December 2019, EU leaders agreed that Europe should achieve climate neutrality by 2050, meaning more ambitious emission reduction scenarios needed to be developed to inform policymakers about possible pathways to achieve this target. The German government adopted this more ambitious climate neutrality target and in 2021, declared that it aimed to achieve the target already by 2045. This climate neutrality target means that industry will need to reduce its GHG emissions significantly faster in the coming decades than previously thought. Instead of GHG emission reductions of some 65 to 80 %, which previous scenarios (e.g. Prognos, EWI, GWS 2014, BDI 2018, EC 2011) found to be in line with overall GHG emission reductions consistent with the lower end of the former target range, more recent global, European and German scenario studies indicate that climate neutrality requires industry sector GHG emission reductions of at least 90 % to 97 % (IEA 2021, EC 2018, BDI 2021, Sensfuß et al. 2021, Günther et al. 2019) relative to 1990 and possibly even of more than 100 % (Prognos/Öko-Institut/Wuppertal Institut 2021, dena 2021).[1]

Technologies, processes and infrastructures used in the industry sector as well as the sector's mix of energy sources may

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[1] In some recent climate protection scenarios for Germany, industry sector GHG emission reductions of more than 100 % relative to 1990 are achieved by combining biomass with carbon capture and storage technology to realise so called "negative emissions". The significant range seen in available scenarios in terms of emission reductions in the industry sector to achieve climate neutrality can be explained mainly by different assumptions about the relative technical and economic potential of emission reductions in the various GHG emitting sectors (including the agricultural sector) as well as by different assumptions about the potential of achieving negative emissions through natural processes in land use, land-use change and forestry (LULUCF).

differ considerably by 2050 depending on whether the sector's GHG emissions need to be reduced by 65 to 80 % or by 90 to 110 %. Given the fact that long investment cycles of several decades are typical for many key production facilities in basic industries, knowledge about feasible pathways towards deep emission reductions are pivotal in order for policymakers to be able to enact policy measures in due time that can keep the window open for reaching climate neutrality by the middle of the century.

We therefore argue that it is important to better understand how transformation pathways compatible with climate neutrality in a narrow sense (i.e. without relying on offsetting of emissions through negative emissions in other sectors or countries) may look like for the industry sector in general and its highest-emitting sub-sectors in particular. This paper aims to contribute to such a better understanding by analysing and comparing industry sector pathways found in several recent climate neutrality scenario studies.

We are not aware of any publications that conduct a meta-analysis of industry sector scenarios compatible with climate neutrality. While several meta-analyses of climate protection scenarios have been performed in recent years, these have mostly not focused on the industry sector, but on the energy system as a whole (e.g. Samadi et al. 2018, Naegler et al. 2021, Wiese/Thema/Cordroch 2021) or on the role of specific energy sources such as biofuels (Chiaramonti et al. 2021) or natural gas (Scharf/Arnold/Lencz 2021).

A previous paper (Samadi/Barthel 2020) performed a meta-analyses of industry sector developments in climate protection scenarios for Germany, Europe and the world. A key finding of this work was that the analysed scenarios pursue many different combinations of mitigation strategies in the industry sector. The authors suggest that this indicates that different pathways towards deep decarbonisation of industry could be feasible and that there is currently no widespread consensus on the most likely or preferred combination of strategies. However, most of the analysed scenarios were not yet aiming for climate neutrality and because of insufficient granularity of some of the scenarios, the paper did not attempt to perform separate analysis of key industry sub-sectors such as steel or cement. Such separate analysis is provided in the paper at hand and is important to better understand the different technology and infrastructural changes required during the transformation of these sub-sectors.

A recently published project paper (SCI4climate.NRW 2021) that performs a meta-analysis of German, European and global scenario and roadmaps specifically for the steel, chemicals and cement sectors is an important basis for the paper at hand, but the selection of scenarios has been updated and the analysis is now limited to German scenarios for the reasons provided in the next section.

This paper is structured as follows: The next section explains how the four studies and five scenarios considered in this meta-analysis were selected. The subsequent section then provides an overview of the similarities and differences between the considered scenarios in regard to key emission reduction strategies pursued by them in the industry sector as a whole. Following this aggregated view of industry sector developments, the subsequent section of the paper looks in detail at differences and similarities of the scenario developments in the three key industry sectors of steel, chemicals and cement. Finally, a concluding section derives the key findings of the analysis and suggests areas for further research.

Selection of studies and scenarios for the meta-analysis

While climate neutrality scenarios have been released in recent years for the world (IEA 2021), Europe (EC 2018, UBA 2019, CAN Europe/EEB 2020) and individual countries other than Germany (e.g. Government of Portugal 2019, Government of the United States 2021), we choose to focus our analysis on four recently released scenario studies for Germany (Sensfuß et al. 2021, BDI 2021, dena 2021, Prognos/Öko-Institut/Wuppertal Institut 2021) for the following three reasons:

- All analysed scenarios from these four studies describe industry sector GHG emission reductions of at least 96 % by 2045 or 2050 relative to 1990, while currently available climate neutrality scenarios for other countries, the European Union or the world describe direct industry sector GHG emission reductions of only some 90 %, relying for the rest on offsetting the sector's residual emissions via natural sinks, biomass CCS in the electricity sector and/or direct air capture with CCS. We argue that it is rather uncertain whether negative emissions of this magnitude can be realised in other sectors or countries in the future and we believe that aiming for a virtually carbon-neutral industry sector is therefore a safer pathway to pursue. This is even more true given the longer-term EU goal of achieving overall negative GHG emissions in the second half of the century.
- Focussing on a uniform geographical area (in our case Germany) ensures that the differences identified between scenarios are not due to variations in geographical characteristics such as current industry structure, resource endowments or societal preferences, but rather due to different perceptions about the most promising or preferable industry sector mitigation strategies. This paper aims to better understand similarities and differences in perceptions about the most promising transformation pathways for a climate-neutral industry sector, while analysis of geographical reasons for differences in strategy and technology choices is left for future research.[2]
- For other geographical areas (other than Germany) no similar number of detailed climate neutrality scenarios could be identified by the authors in the available literature.

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[2] A potential drawback of such a small geographic scope could be that country-specific scenarios may assume significant domestic production declines of basic materials, compensated by higher imports. This could lead to considerable emission reductions in the scope of the studies, but would also result in higher emissions or additional mitigation challenges in exporting countries. In this regard, however, the structure of Germany's heavy industry is beneficial, as Germany is not dependent on (significant) net imports of most basic materials. Furthermore, the scenarios analysed assume relatively constant future production volumes in Germany, meaning that no significant relocation effects are assumed. One exemption is high-value chemicals, where several studies foresee declines in German production due to changes in the location of fuel and feedstock production.

Table 1. Overview of the four studies and five scenarios selected for the meta-analysis.

Study name and literature reference	**Scenario developer(s)**	**Year published**	**Scenario(s) included in this paper's meta-analysis**	**Change in GHG emissions by 2050 (relative to 1990)**	
				Total	Industry
dena pilot study Towards Climate Neutrality (dena 2021)	EWI	2021	KN100	– 102 %	– 104 %
Climate Paths 2.0 – A Program for Climate and Germany's Future Development (BDI 2021)	BCG	2021	Target Path	– 100 % (2045)	– 96 % (2045)
Towards a Climate-Neutral Germany by 2045 (Prognos/Öko-Institut/ Wuppertal Institut 2021)	Prognos, Öko-Institut, Wuppertal Institut	2021	CN2045	– 102 %	– 111 %
Long-term Scenarios for the Transformation of the Energy System in Germany (Sensfuß et al. 2021)	Consentec, Fraunhofer ISI, ifeu, TU Berlin	2021	TN-Strom	– 102 %	– 97 %
			TN-H_2-G	– 101 %	– 97 %

The four German scenario studies were chosen based on the following criteria:

- Studies must include at least one scenario that describes a pathway towards overall net zero GHG emissions in Germany by no later than 2050.
- The studies' scenarios must include assumptions about the development of all main GHG emitting sectors (energy, industry, buildings, transport, agriculture), so as to be able to describe a GHG reduction pathway for the industry sector that could be in line with overall climate neutrality.
- The studies' scenarios must include specific information about developments in the key sub-sectors of steel, chemicals and cement, as we intend to analyse these sub-sectors in detail in this meta-study due to their high current shares in total industry sector GHG emissions.[3] Scenarios needs to include at least sub-sector data on energy use by sources, production processes applied and greenhouse gases emitted.
- The scenario studies need to have been released no earlier than 2020 in order to reflect the most recent knowledge about GHG emission reduction potentials in the industry sector.[4]

Table 1 provides an overview of the four scenario studies and five scenarios included in this meta-analysis.

While another scenario study (Prognos/Öko-Institut/Wuppertal Institut 2020) fulfilled all four criteria listed above, it was decided not to include the study's scenario in this meta-analysis as the follow-up study's scenario (Prognos/Öko-Institut/Wuppertal Institut 2021) is already included and is very similar. The main difference between both scenarios is the year in which climate neutrality is reached – 2050 in the older study and 2045 in the newer study included in this meta-analysis. Another recently released scenario study describing a pathway towards climate neutrality in Germany by 2045 (FZ Jülich 2021) was not taken into consideration because it does not provide details regarding developments in the sub-sectors of steel, chemicals and cement.

Two of the four studies considered provide only one scenario that reaches GHG neutrality, while the study on behalf of dena (2021) includes one main scenario and several scenario variants. In this paper's meta-analysis, only the main scenario is included for reasons of clarity and brevity. For the same reason, of the three scenarios included in the study on behalf of BMWi (Sensfuß et al. 2021), only two are included in this meta-analysis. The study's scenario TN-PtG/PtL is not included as it is generally very similar to its scenario TN-H_2-G, with the main difference in the end-use sectors being that much of the hydrogen demand of the TN-H_2-G scenario is assumed to be met by synthetic fuels.[5]

The four studies' methodological approaches to developing the scenarios are generally similar. While specific details of each study's modelling instruments may differ and are not elaborated in detail in all of the studies, all studies use several sector-specific and technologically detailed bottom-up models to derive possible sectoral developments. Existing energy and climate targets of the German government are typically respected by the scenarios, which is one reasons why these scenarios are not developed based on a purely cost-optimizing approach. Apart from government targets, assumptions about the social acceptance of various technologies and infrastructures are also typically taken into account by the scenario modelers.

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[3] In both Germany and the EU27, these three sub-sectors were responsible for well over half of all industry sector GHG emissions in the year 2017 (Agora Energiewende/Wuppertal Institut 2019, 2021).

[4] In any case, studies published before 2020 usually do not contain scenarios that achieve climate neutrality by 2050.

[5] The authors themselves refer to the TN-PtG/PtL scenario as a "very special case" and a "marginal scenario" ("Randszenario" in German) (Sensfuß et al. 2021).

Comparison of sector-wide developments

This first part of this meta-analysis focuses on similarities and differences between the analysed scenario in respect to the industry sector as a whole. Figure 1 depicts industry sector GHG emission developments in the five scenarios until 2050. It shows that emission reductions until 2030 (relative to 1990) are somewhat similar in all scenarios, ranging from -54 % to -59 %. Two of the scenarios (Target Path and KN100) comply with the GHG reduction target of the industry sector, which the German government tightened in mid 2021 to -58 %, while the other three scenarios narrowly miss the target. However, by 2040 the development of GHG emissions vary more strongly between the scenarios, with the CN2045 scenario describing significantly lower emissions than the other four scenarios.

The CN2045 scenario developers see a need for achieving net negative emissions in the industry sector by 2045 in order to compensate for non-abatable emissions foreseen in the agricultural sector. While the other analysed scenarios also see a general need for negative emissions by 2045/2050 – with all analysed scenarios envisioning a need of some 60 to 80 Mt of annual CO$_2$ equivalents (see Figure 2) – they expect these negative emissions to come to a much smaller extent (KN100, Target Path) or not at all (TN-Strom, TN-H$_2$) from industry.

The authors of the CN2045 scenario explain the significant negative emissions from industry by emphasising the high uncertainties in regard to future LULUCF contributions as well as the relatively small costs of using biomass in combination with CCS at certain large industrial facilities. In the two analysed TN scenarios, on the other hand, relatively optimistic assumptions about negative emissions from LULUCF as well as about the future use of negative emission technologies (not further specified in the study, but here assumed to be direct air capture) mean that in these scenarios, there are still net residual emissions from industry in 2050 (see Figure 1).

The following Table 2 provides an overview of the reliance on key industry sector GHG emission reduction strategies in the analysed scenarios. The distinction of strategies is based on Samadi/Barthel (2020), which also provide a short explanation of each strategy.

Table 2 indicates that despite the strong reductions in industry sector GHG emissions observed in all analysed scenarios, there are considerable differences between the scenarios in how these emission reductions are achieved. In fact, it can be argued that uncertainties regarding the most promising or most desirable mix of mitigation strategies are strongest in the industry sector compared to both the energy sector as well as the other end use sectors of the energy system.

On the energy supply side, all scenarios envision a stronger use of electricity in final energy demand and a relevant role for hydrogen. By 2045/2050, all hydrogen used in the scenarios is green – that is sourced from renewable electricity, but CCS-based blue hydrogen is also assumed to be used for a limited time in some of the scenarios. In all scenarios, most of the hydrogen used in the industry sector is utilised in the steel and chemical industries, both for energetic and non-energetic purposes. The scenarios differ in respect to how much hydrogen is used for providing process heat in other industry sectors. An outlier in this respect is the very strong use of hydrogen in various industrial sub-sectors in the scenario TN-H$_2$-G. In line with its storyline of focussing on hydrogen, much of the required process heat in this scenario is provided by hydrogen, while the other scenarios rely to a much stronger extent on electricity or biomass to provide process heat.

The use of synthetic fuels (or e-fuels) produced from electricity from renewable energy sources varies among scenarios.

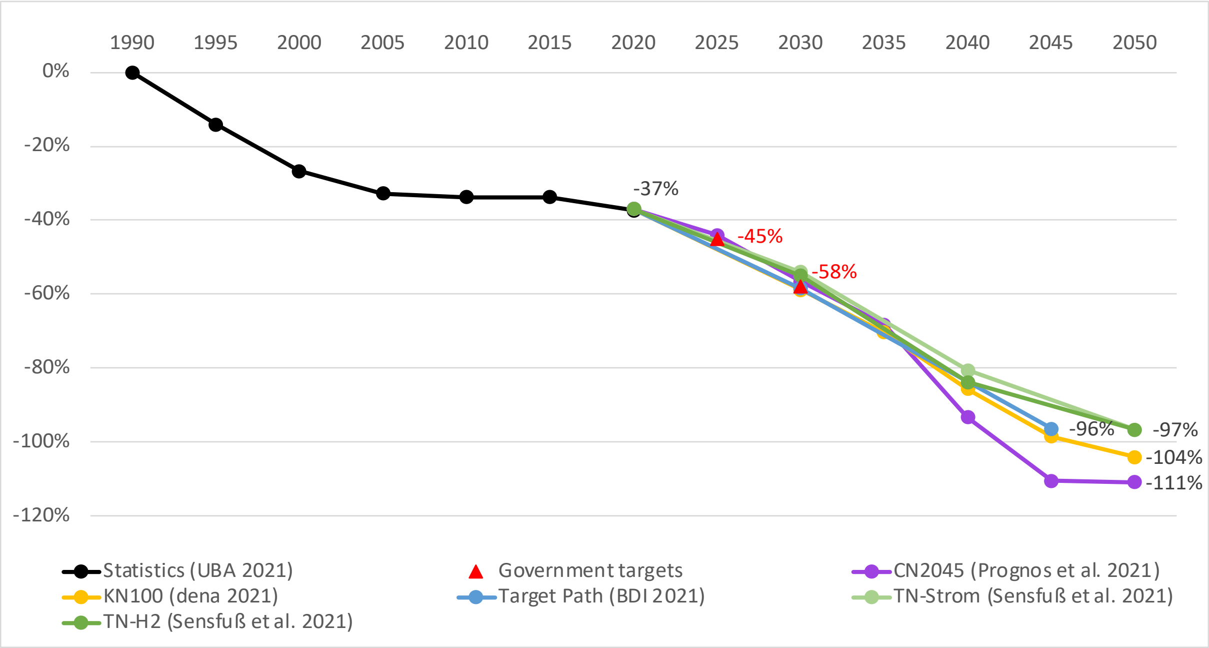


Figure 1. Development of industry sector GHG emissions relative to 1990 in the analysed scenarios.

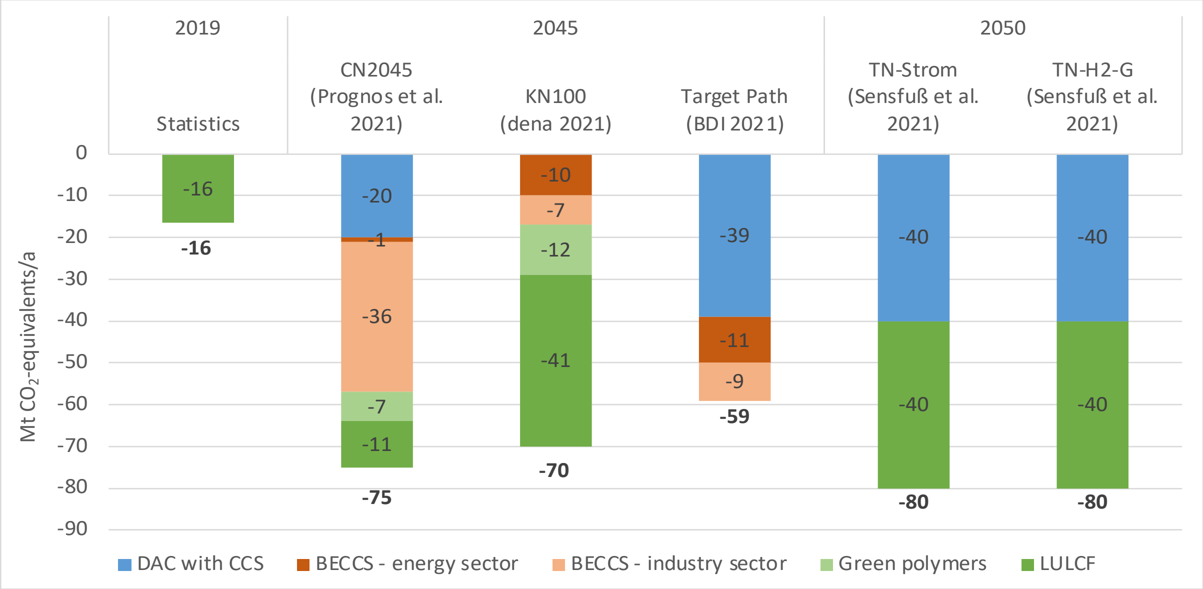


Figure 2. Negative emissions and their sources in 2019 and in the analysed scenarios in 2045/2050.

Table 2. Overview of the relevance of key industry sector emission reduction strategies used until 2045/2050 in the analysed scenarios.

Strategy	**CN2045** (Prognos et al. 2021)	**KN100** (dena 2021)	**Target Path** (BDI 2021)	**TN-Strom** (Sensfuß et al. 2021)	**TN-H$_2$-G** (Sensfuß et al. 2021)
Direct electrification	++	++	+++	+++	+
Use of hydrogen*	+	++	+	++	+++
Use of synthetic energy carriers*	+	+	++	**n.s.**	**n.s.**
Use of biomass	+++	++	++	**o**	**o**
Use of CCS	++	+	++	**o**	**o**
Use of BECCS	+++	+	+	**o**	**o**
Increase in energy efficiency	++	++	++	++	++
Increase in material efficiency	+	+	**o**	+++	+++
Increase in recycling rates	++	+	+	+++	+++
Material substitution	+	**o**	+	+	+
End-use demand reductions	**o**	**o**	**o**	**o**	**o**

**includes energetic and non-energetic use.*

Only in the Target Path scenario synthetic fuels are used for final energy purposes in the industry sector, to a relevant extent. However, in all scenarios, synthetic hydrocarbons are used as a feedstock source in the chemical industry.

Biomass in the industry sector is used most strongly in the CN2045 scenario. This is mainly due to the aforementioned strategy of achieving negative emissions by using biomass in combination with CCS technology, mostly in large-scale plants of the chemical and steel sectors. Biomass is also used much more strongly than today in the industrial sector in the KN100 and the Target Path scenarios. In these scenarios, biomass is also used to achieve negative emissions through BECCS, but to a smaller extent than in CN2045. It is also used generally (without CCS) in these scenarios for providing process heat in various industrial sub-sector.

The lack of CO_2 storage of industrial emissions in both analysed TN scenarios is compensated in these scenarios by more optimistic assumptions about future negative emissions in the LULUCF sector and through other (non-specified) negative emission technologies such as direct air capture.

Future improvements in energy efficiency apparently play an important role in all scenarios, although this strategy is difficult to compare among the scenarios. As an (imperfect) proxy for energy efficiency, we look at the changes in final energy intensity in all scenarios between their respective base years and 2045/2050. Final energy intensity, defined here as industrial final energy demand per industrial gross value added, improves to a similar extent in all scenarios analysed (average improvements of 1.6 to 1.7 % per year) and is slightly above the average annual rate of improvement observed in Germany between 2000 and 2019 (1.5 %).

Improvements in material efficiency are assumed for several basic materials in the TN scenarios. In these scenarios, for example, by 2050 paper demand is assumed to be 10 % lower than in a reference development as a result of a trend towards more paperless applications, while cement demand, container glass demand as well as plastics demand is reduced by 15 % each through efficiency improvements in construction (cement) and more efficient product design. In the other three scenarios, only few assumptions can be found on material efficiency improvements as an explicit strategy to reduce energy demand in the industry sector. The only exception is the particularly difficult-to-abate cement sector: In the CN2045 scenario, cement demand is reduced by some 20 %, mainly through material-saving construction methods and a more efficient use of cement in concretes. KN100 and Target Path likewise foresee cement demand reductions through material efficiency improvements, albeit to a lower extent than in CN2045 and the TN scenarios.

The substitution of certain materials through less energy and emission-intensive materials does not seem to be regarded as a very promising strategy to reduce industry sector GHG emissions in any of the analysed scenarios. However, the two TN scenarios briefly mention material substitution as a strategy to achieve (modest) reductions in future steel demand relative to a reference development, while in the Target Path and the CN2045 scenarios, future cement demand is assumed to be reduced to a limited extent by substituting its use by other materials, with the CN2045 scenario explicitly mentioning a stronger use of wood in construction.

None of the scenarios assume future reductions in end use demand, such as lower demand for consumer goods, to reduce industry sector emissions relative to a reference development. One reason for this may be the fact that demand and production for industrial goods are only loosely linked on a national level because a substantial share of domestically used goods is imported, while a large share of domestic production is exported.

In-depth look at the steel, chemicals and cement subsectors

Figure 3 provides insights into the assumptions on future production routes and energy demand of crude steel production in Germany. For clarity, only data for 2020, 2030 and 2050 are given.

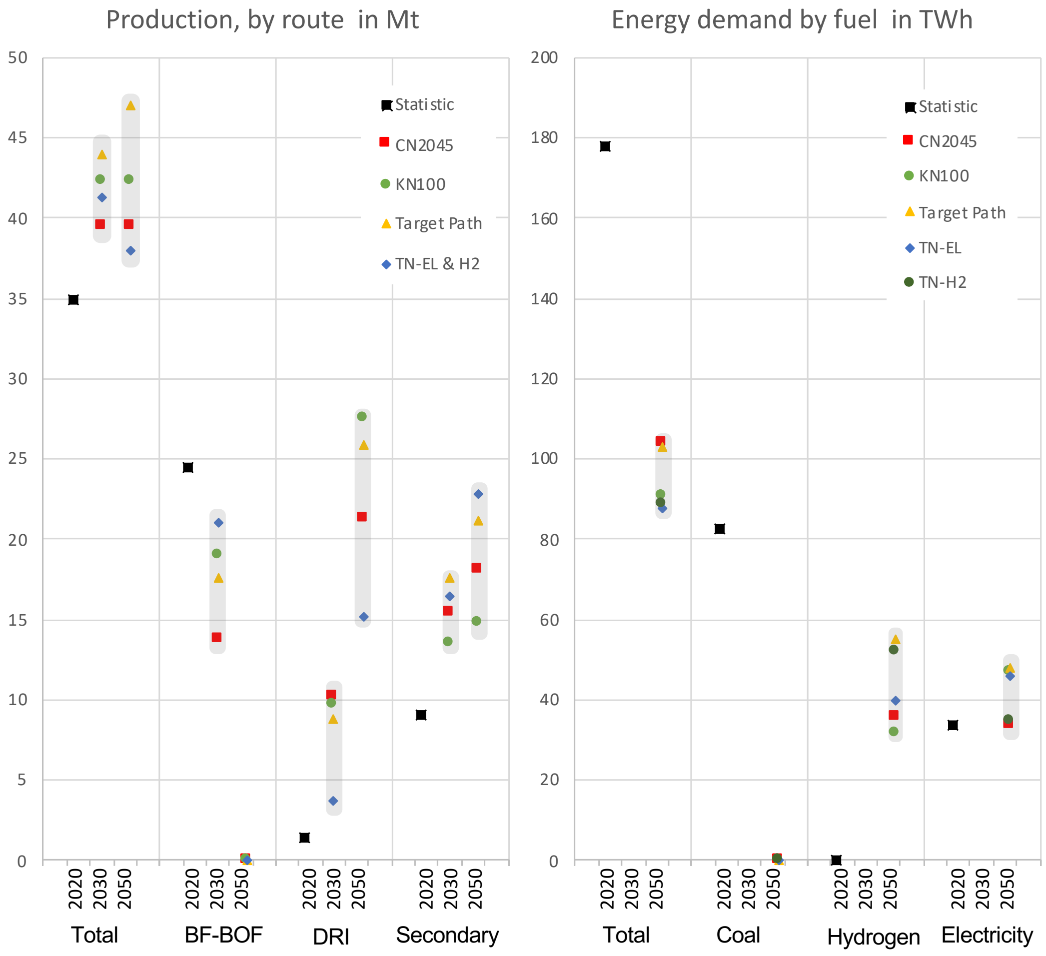


Figure 3. Crude steel production by route and resulting energy demand, comparison of scenarios for Germany for 2020, 2030 and 2050.

The comparison of the scenarios shows that while there are significant differences, all scenarios also assume some similar future trends of steel making in Germany:

- Overall production is assumed to recover from its low 2020 level back to a range of 40 to 45 Mt in 2030 and a slightly larger range in 2050, with two studies assuming stable, one growing and one slightly declining production levels. This means that Germany will continue to produce at least as much steel as it consumes.
- Studies are generally in line regarding growing shares of secondary steel, which is assumed to increase from a current share of roughly a third of production to between 40 and 60 % by 2050 in all scenarios.
- In all scenarios, blast furnaces are phased out and primary steel production is completely converted towards hydrogen-based direct reduction technology by 2050. The speed of conversion, however, differs between the scenarios, with most assuming already 8 to 10 Mt steel being produced in 2030 in direct reduction plants but two scenarios (TN-Strom, TN-H_2-G) from a single study only expect 3.5 Mt by that date.
- Among the scenarios, the TN-Strom and TH-H_2-G scenarios seem to be slight outliers, with lower production levels, significantly higher secondary steelmaking as well as a slower introduction of new primary steel making assets.

Regarding the energy supply of steel industry, similarities between the scenarios are even more pronounced:

- Due to the complete switch to the more energy-efficient direct reduction process in primary steelmaking as well as the increasing shares of secondary steelmaking, energy demand of the steel industry declines by roughly 50 % relative to today, to between 85 and 105 TWh by 2050.
- The bulk of the energy demand will be met by hydrogen, of which between 35 and 58 TWh will be used by 2050. One of the analysed scenarios (CN2045) also relies strongly on biomass, combining its use with carbon capture and storage in order to achieve negative emissions, as explained in the previous section. Electricity demand for steel production either remains stable in the scenarios or grows by roughly a third.

For the steel industry, the scenarios thus present a relatively consistent outlook. Little change is assumed in regard to the level of domestic production. The share of secondary production, however, is assumed to increase, but to quite different extents with a range of 40 to 60 % by 2050. The slightly declining primary steel production, however, is assumed to be fully converted to hydrogen based zero carbon production in all scenarios, with most of them already expecting a quarter of total German steel production through this route by 2030.

The chemicals industry is more complex and diverse than the steel and cement industries and the scenarios also show greater divergence in their pictures of a climate neutral chemical industry.

This divergence starts with their outlooks on the physical production of the two main groups of basic chemicals, ammonia (mainly used to produce fertilizer) and high-value chemicals (HVC), used to produce all sorts of plastics and other organic chemicals.

- The scenarios provide a significant range of future developments, from assuming an almost stable future production to assuming a reduction in production volumes by more than a third by 2030 and by over 40 % by 2050.
- These numbers mean that the scenarios are split between an outlook in which Germany will remain (on a net basis) more or less self-sufficient with regards to high-value chemicals and ammonia and one with higher import shares of basic chemicals. However, regarding chemical products in general, Germany is assumed to remain a net exporter.

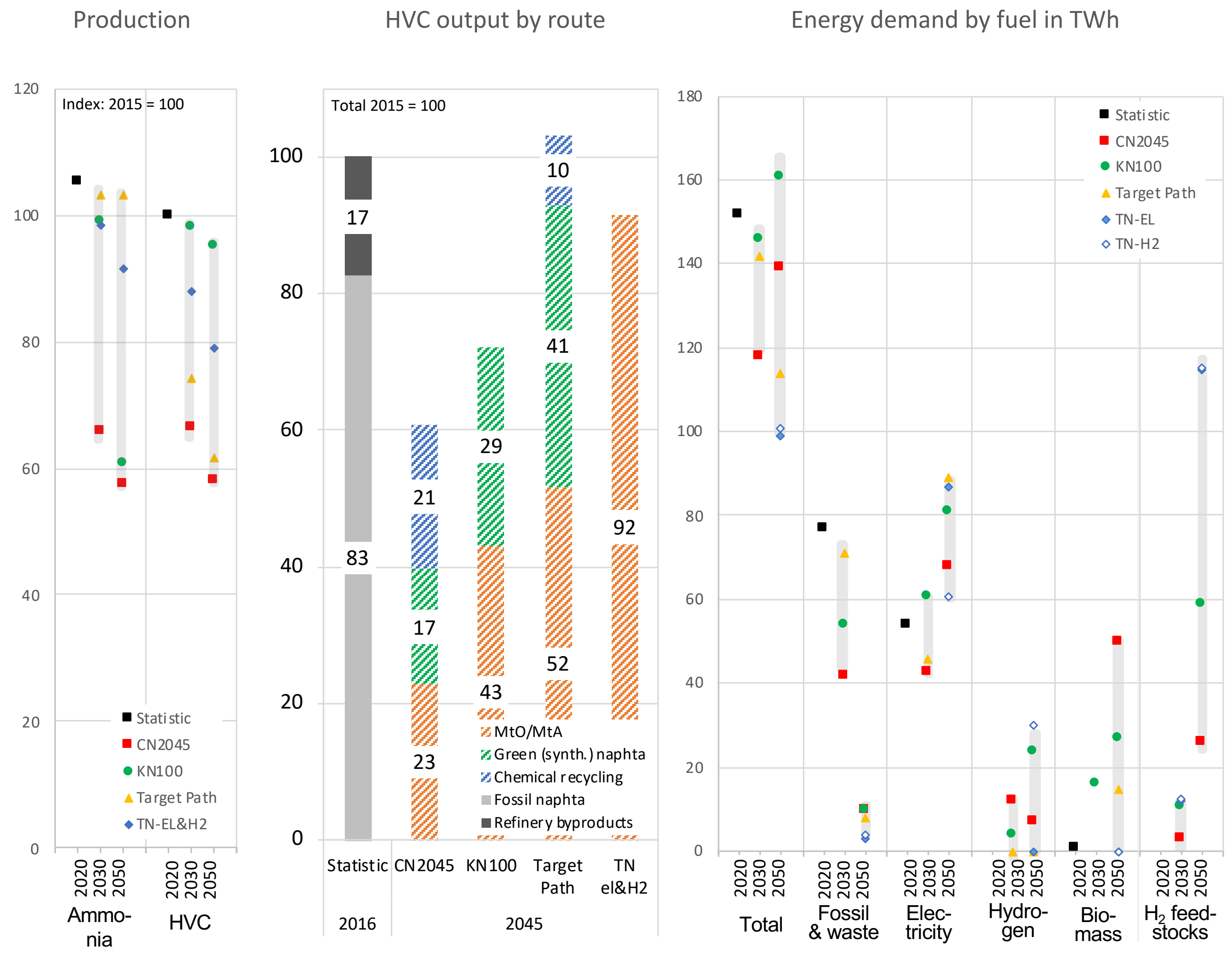
Regarding production technologies, all scenarios assume that ammonia production will be converted from today's dominant feedstock of natural gas towards green hydrogen as a feedstock. This conversion is assumed to be rather straightforward as hydrogen is already the core intermediate when producing ammonia (NH_3). As not all studies provide demand estimates, it is assumed here that the main reason explaining differences in production volumes of ammonia are differences in the assumed share of future imports. However, the CN2045 additionally assumes that domestic ammonia production in Germany will shrink due to the transformation of agriculture and a resulting decrease in the need for nitrogen-based fertilizers in Europe.

For the HVCs, all studies assume that the current fossil routes (based on naphtha from crude oil and refinery by-products) will be completely phased out by the middle of the century. By then, production will either be based on the methanol-to-olefins (MTO) route, the methanol-to-aromatics (MTA) route or on the green naphtha route. The MTO and MTA routes use methanol as a basic feedstock derived from green hydrogen and carbon for organic chemistry. The green naphtha route relies on the same feedstock but uses the Fischer-Tropsch synthesis. This route produces a yield spectrum which is closer to the current fossil-based naphtha and thus might require less downstream adaptation in the diverse chemical industries. Only two of the scenarios also assume significant shares of chemical recycling (via pyrolysis and gasification), which uses recycled plastics to produce feedstock for new organic compounds.

The scenarios differ significantly with regards to the assumed share of the three climate neutral HVC production routes. While one study fully bets on MtO/MtA the other studies all see a mix of a larger share of MtO/MtA with slightly less green naphtha. Two scenarios also expect chemical recycling to deliver significant amounts of HVCs, equivalent to between 10 and 20 % of current fossil production. For green naphtha, assumed volumes for 2045 range from 17 to 41 % of todays total fossil production and for MtO/MtA the range is from 23 to 92 %.

Again, increasing imports are the main reason for the big differences in assumed future production volumes. These differences in production routes and domestic production volumes demonstrate how significantly the views on future HVC production in Germany still diverge. An important consequence of these considerable differences is the strong spread in the total amount of hydrogen needed for feedstocks by the middle of the century. While the CN2045 scenario assumes less then 30 TWh, the TN-H2 scenario (which completley focusses on the MtO/MtA route) expects a feedstock demand of around 115 TWh H_2.

The future energy demand of the chemical industry ranges from 100 to 160 TWh by 2050, which is larger than the as-



Production

HVC output by route

Energy demand by fuel in TWh

Figure 4. Production of basic chemicals by route and related energy & feedstock demand by energy carrier 2020, 2030 and 2050.

sumed differences in physical production. Also, both trends only weakly correlate. However, for the CN2045 scenario with lowest production volumes this can be explained by high biomass use and the energy penalty of the related BECCS (see negative emissions). Regarding the fuel split, all studies expect increasing electrification, albeit to a different extent. Absolute growth ranges from 10 to 90 % between 2020 and 2050. While the use of fossil fuels and waste obviously declines to close to zero in all scenarios, they are split regarding the energetic use of hydrogen (between 0 and 30 TWh in 2050) and the use of biomass, with two scenarios relying on high amounts of hydrogen and no biomass while the others use biomass but little or no hydrogen for energetic purposes (see also the discussion in the previous section).

Overall, these comparisons show that for the chemical industry, scenario assumptions and results vary significantly, although the main strategies of electrification and the use of climate neutral hydrogen and hydrocarbons as feedstock are similar. Key differences between the scenarios are varying assumptions on future imports of already manufactured green HVCs (which reduce the need for the domestic use of hydrogen as feedstock), on production routes and on the role of hydrogen and biomass as energy carriers.

Compared to steel making and basic chemicals, cement making is a much smaller sector. It is, however, also highly emitting. Figure 4 displays major mitigation trends in cement making. As in the other sectors, the scenarios generally rely on a similar suite of emission reduction levers, but each lever's relative role as well as the low carbon energy mixes assumed vary significantly between the scenarios:

- Production is on average expected to slowly decline by some 3 Mt by 2030 and another 3 Mt by 2050, with three scenarios (TN-Strom, TN-H_2-G, CN2045) attributing roughly 50 % of the decline by 2050 to active demand reduction measures to reduce concrete and cement demand in buildings and the rest resulting from reduced building activity.
- As clinker is the main emission intensive component, its share in overall production matters. Scenarios assume further declines in clinker content of cement from 72 % in 2020 to a range of 55 to 66 % by 2050. To achieve this further decline of the clinker share it is assumed that alternative binding materials will be used to substitute not just clinker but also the steel mill slag that will no longer be available by the middle of the century due to the phase out of the fossil-based blast furnace route in steelmaking.

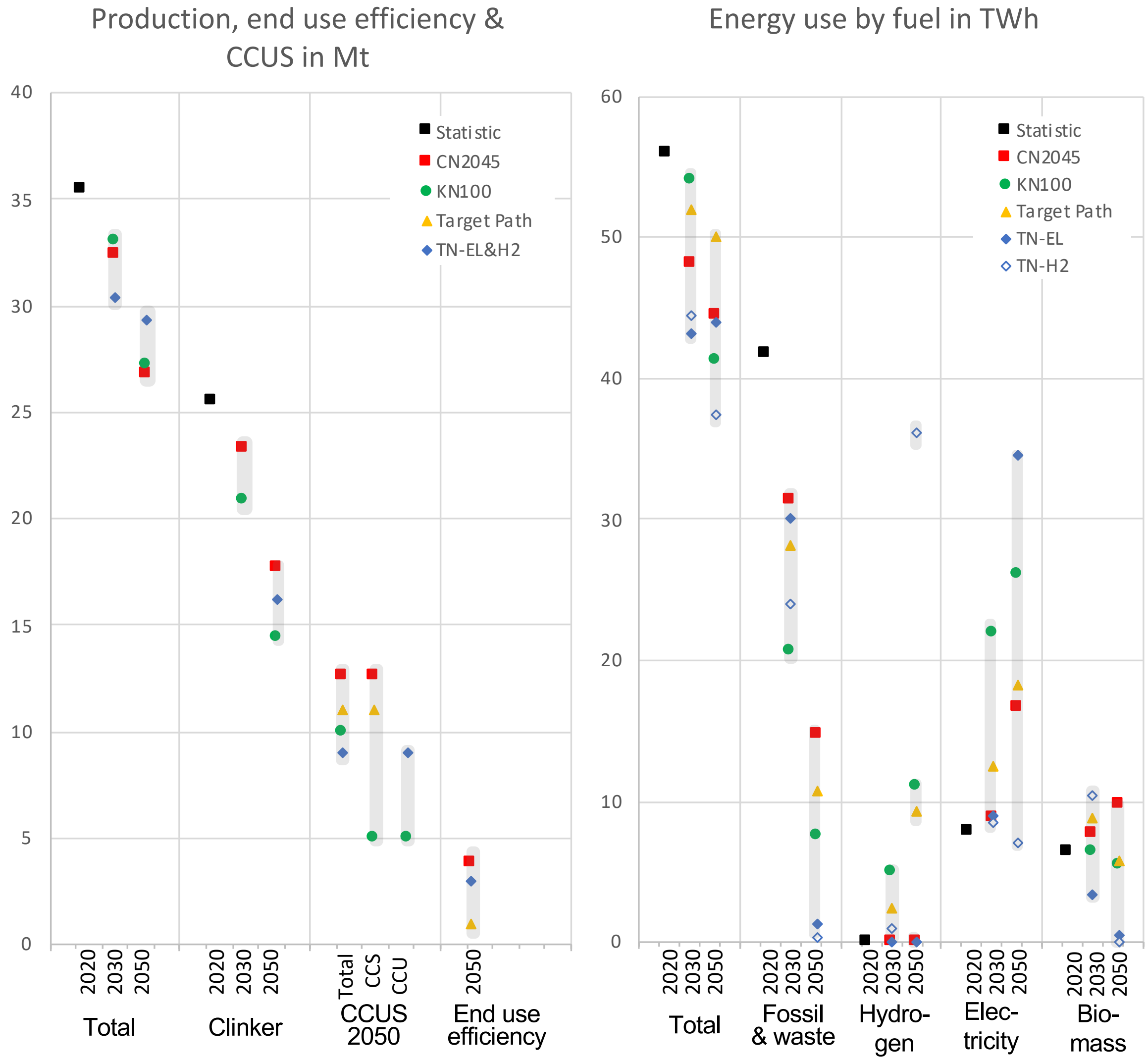


Figure 5. Cement and clinker production, CCUS and energy demand, comparison of scenarios for Germany for 2020, 2030 and 2050.

- The remaining process-related emissions of 8 to 10 Mt of CO_2 from clinker burning are captured for the most part in all scenarios, together with energy-related emissions from fossil waste and biomass. The CO_2 is then assumed to be either stored permanently or used in the chemical industry.
- Energy demand of the cement industry is expected to decline in the scenarios. However, specific energy demand varies somewhat between the scenarios, which can be explained at least in part by diverging energy penalties due to different volumes of carbon capture.
- The energy mix in 2050 also differs between the scenarios, with different shares of electricity, fossil waste, biomass and hydrogen. The latter is used in cement production only in three of the five analysed scenarios.

Conclusion

This paper's meta-analysis of industry sector developments in recent climate neutrality scenarios for Germany is particularly relevant as German scenarios are highly ambitious, picturing pathways towards 100 % technical emission reductions in industry without offsetting and without major shifts from domestic production to imports for energy intensive goods. Our analysis illustrates that there are notable similarities but also a few relevant differences between the scenarios.

Key agreements between the scenarios include:

- It is *technologically feasible to achieve net emission reductions of at least 96 %* (relative to 1990) in the German industry sector by 2050 the latest, using only available technologies or technologies expected to be ready for use on a sufficiently large scale in the near future. No widespread relocations of the basic material industry or offsetting measures are assumed for achieving such emission reductions.
- *Electricity demand for the industry sector will increase considerably*, both for the direct use of electricity as well as for the indirect use in the form of electricity-based hydrogen and synthetic fuels. Compared to today, the sum of the required electricity for the industry sector (i.e. its direct and indirect use) more than doubles in all analysed scenarios by 2045/2050 and more than triples in at least three of the

five scenarios. This emphasises that climate neutrality in the industry sector depends heavily on the successful ramp-up of renewable electricity capacities in Germany and abroad (for imports).

- *Industrial carbon capture and storage appears to be needed* to a certain extent in all analysed scenarios. Three of the five scenarios assume that carbon capture and storage will be used for both fossil and biogenic CO_2 emissions from industrial plants, most notably from cement and lime production plants. The other two scenarios assume that "negative emission technologies" will be used to a significant extent, which we assume will likely be Direct Air Capture with CCS, meaning that these DAC plants will "indirectly" capture and store residual emissions from industry. This indicates that policymakers and society should discuss in an open manner the extent to which CCS should be used and what steps are needed in the short- to mid-term to ensure that the required CO_2 infrastructure will be in place in time.
- *Further improvements in energy efficiency as well as higher recycling rates* are assumed in all scenarios to help mitigate the increasing demand for climate-neutral energy sources.
- Reductions in material demand or substitutions of higher emitting materials by other, lower emitting materials are hardly assumed in the scenarios, with only small exceptions. Reasons for this may be scepticism about the feasibility or effectiveness of these strategies, but could also be due to the fact that domestic production in most sectors is heavily interconnected with international value chains, meaning that domestic demand reductions do not necessarily lead to similar reductions in domestic production. (In the cement sector with much less international trade, some measures are assumed in the scenarios.)
- *Primary steel making is broadly expected to switch entirely to the hydrogen-based direct reduction route.* Contrary to this finding, recent global (IEA 2021) and European (EC 2018) climate neutrality scenarios envision a broader mix of low-CO_2 primary steelmaking processes. While these international scenarios also foresee an important role for hydrogen direct reduction, they also rely on coal-based CCS processes as well as iron ore electrolysis. However, the focus on hydrogen based DRI in the German scenarios is in line with current announcements by large German and European steelmakers, while no announcements have been made to invest in any of the alternative routes (Witeka et al. 2021).

Key differences between the scenarios include:

- There is considerable *disagreement among the scenarios about the relevance of different (largely) carbon-neutral final energy sources* in 2045/2050, most notably electricity, hydrogen and biomass. This reflects the general flexibility in much of the industry in using different energy sources for generating process heat. The question of which carbon-neutral energy source to use to what extent is closely related to the overall energy system and other GHG emitting sectors. A stronger use of hydrogen instead of electricity, for example, while associated with efficiency losses, can reduce the burden on the electricity supply and distribution system by reducing the need for baseload electricity.
- The *use of biomass*, on the other hand, can contribute to negative emissions when combined with CCS, providing an opportunity to compensate non-abatable emissions in some parts of the industry and other sectors such as agriculture. Different assumptions about the mitigation potential in other sectors (especially in the agricultural sector) can therefore indirectly influence the preferred choice of final energy sources in the industry sector.
- There are also *different assessments on how much recycling rates can be increased*. This is especially relevant for the steel and chemical industry. In the case of steel, uncertainties still exist in regard to future volumes and qualities of scrap and future capabilities to transform this scrap into high-quality primary steel. In the case of plastics, some of the analysed scenarios do not assume any chemical recycling to take place by 2045/2050, while one of the scenarios relies strongly on chemical recycling to reduce end-of-life emissions of plastics and to source feedstock for high-value chemicals production.
- Particularly for basic chemicals, studies present strongly diverging domestic production volumes as well as diverging technological routes for high-value chemicals. This shows that the effects of deep GHG emission reductions in the sector are still very uncertain and quite diverse scenarios can be imagined. As different scenarios can lead to strongly diverging demands for electricity and particularly hydrogen, the future development of the sector is highly interlinked with that of the energy system.

These differences also point towards future research needs:

- Further studies should try to shed light on the complex interdependencies between the industry system and the energy supply system, finding out how decisions in the industry sector, including the choice of final energy sources, may benefit or complicate deep and swift emission reductions in the energy supply sector or how uncertainties about future availability of hydrogen and synfuel imports may influence mitigation pathways in the industry sector.
- Linked to this is a need to better understand interdependencies between deep decarbonisation in the basic industries and locational effects. The existing differences in the geographical distribution of renewable energy sources could become a driver for significant changes in the locations of basic materials production and related value chains ("Renewables Pull"), which in turn would influence the future energy systems of countries like Germany (cp. Samadi et al. 2021, Gielen et al. 2020).
- A better understanding of the potential to reduce GHG emissions in the agricultural sector or to use negative emission technologies such as DAC would also lead to a better understanding of the required reductions as well as the need to generate negative emissions in the industry sector. This in turn will have repercussions on industry sector technology choice.
- In addition, further research is needed to better understand the future potential of increasing recycling rates, including steel scrap recycling and mechanical as well as chemical re-

ANNEX

Annex table: Quantification of some of the key industry sector emission reduction strategies used until 2045/2050 in the analysed scenarios.

Strategy	**Indicator**	**Statistics**		**CN2045** (Prognos et al. 2021)	**KN100** (dena 2021)	**Target Path** (BDI 2021)	**TN-Strom** (Sensfuß et al. 2021)	**TN-H_2-G** (Sensfuß et al. 2021)
		2000	**2019**	**2045**			**2050**	
Direct electrification	Electricity use in TWh	209	218	317	311	400	404	235
Use of hydrogen	Hydrogen use (energetic and non-energetic) in TWh	0	0	74	190	96	156	359
Use of synthetic energy carriers	Use of synthetic energy carriers (energetic and non-energetic) in TWh	0	0	35	51	173	n. s.	n. s.
Use of biomass	Biomass use in TWh	4	31	171	88	94	1	1
Use of CCS	Fossil CO_2 stored in Mt	0	0	16	7	11	0	0
Use of BECCS	Biogenic CO_2 stored in Mt	0	0	36	7	9	0	0
Use of CCU	CO_2 utilized in Mt	0	0	0	10	n. s.	9	7
Increase in energy efficiency	Change in final energy intensity (final energy demand per industrial gross value added)	-1.5%/a (2000-2019)		-1.7%/a (since 2016)	-1.7%/a (since 2018)	-1.7%/a (since 2019)	-1.7%/a (since 2015)	-1.6%/a (since 2015)

cycling of plastics. Besides the potential of increasing recycling rates, the complexity associated with material flows in modern societies also means that more research is needed on specific steps that need to be taken to actually achieve higher recycling rates.

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