Stiftung Klimaneutralität
Agora Energiewende
Agora Verkehrswende

Towards a Climate-Neutral Germany by 2045

How Germany can reach its climate targets before 2050

EXECUTIVE SUMMARY

prognos
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Institut für angewandte Ökologie
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Wuppertal Institut

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In addition to overseeing the building and energy sectors in this study, Prognos was entrusted with overall project management and scenario design. Öko-Institut was responsible for transport, agriculture, waste and LULUCF (land use, land use change and forestry), as well as the derivation of emission reduction targets. The Wuppertal Institut was responsible for examining the industrial sector.

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Preface

Dear readers,

The race is on. With the Biden administration in office, the world's largest greenhouse gas emitters – China, the US, and the EU – are now focused on achieving net zero. The dramatic policy shift in the US speaks to the building global momentum. The US now aims to achieve a carbon-free power system by as early as 2035. Indeed, climate policy pervades the US government's actions with greater stringency than ever before.

The global community is in a race against time to achieve climate neutrality. The extreme weather events that climate scientists predicted years ago are already occurring with alarming frequency, causing economic damage and human suffering on a dramatic scale.

Against this backdrop, the obvious question is whether we can accelerate our climate protection efforts. How can we achieve climate neutrality well before 2050? This study provides the answers. The previous report, "Climate-Neutral Germany 2050", showed how the zero-carbon target adopted by the German parliament (Bundestag) can be achieved by the middle of the century. This study, by contrast, shows how climate neutrality is possible by as early as 2045.

We follow the basic approach of the original study, charting a realistic path to climate neutrality that respects asset lifetime and investment-cycles while ensuring cost-effectiveness and public acceptance. Our revised timeline for carbon neutrality in the post-2030 period is based on the rapid expansion of the hydrogen economy, a more dynamic electrification of the transport sector, an increased rate of green retrofits for buildings, and a faster transition from animal- to plant-based proteins.

So can we achieve net-zero emissions before 2050? The answer is an emphatic "yes". In doing so, Germany could leverage the global dynamics towards climate-neutrality particularly well and position itself as a lead market and technology provider. Whether we *will* be climate-neutral as early as 2045 is ultimately a question of our collective political will and our society's ability to find creative solutions.

We hope you enjoy reading this study.

Rainer Baake, *Director, Climate Neutrality Foundation*
Dr. Patrick Graichen, *Director, Agora Energiewende*
Christian Hochfeld, *Director, Agora Verkehrswende*

Key findings at a glance:

1. **A climate-neutral Germany is possible as early as 2045. Compared with the 2050 goal, achieving climate neutrality by 2045 avoids almost one billion tons of CO_2 emissions.** This would re-establish Germany as an international leader in climate protection and make it a lead market and technology provider for climate-friendly technologies.

2. **An emissions reduction target of 65% for 2030 is a suitable milestone on the path to climate neutrality by 2045,** and would set the stage for an accelerated transformation after 2030.

3. **Climate neutrality by 2045 means more rapid structural transformation:** After 2030, the transformation would have to accelerate with regard to renewable energy expansion, industrial decarbonisation, and the adoption of heat pumps and electric vehicles. The transformation of the agricultural sector and the use of carbon capture and storage (CCS) technologies will have to occur sooner.

Content

Introduction

The 2020 study "Climate-Neutral Germany 2050" laid out an economically sound strategy to achieve Germany's official, parliament-approved 2050 climate-neutrality target. Climate neutrality results from a complete or near-complete avoidance of greenhouse gas emissions and the compensation of any residual emissions via negative emissions, i.e. the removal of atmospheric carbon and its subsequent sequestration.

With the new „Climate-Neutral Germany 2045" scenario, we go a step further and answer the question of whether climate-neutrality is already possible in 2045 - with a "yes". The present study also describes a strategy preserving investment cycles and without politically imposed behavioral changes. The current study shows that on the basis of the already ambitious target of a 65 percent greenhouse gas reduction by 2030, an accelerated transformation is subsequently possible and necessary in all sectors.

Achieving climate-neutrality already by 2045 would bring two major benefits: The new target would reduce the cumulative emissions released by Germany by 900 million tons of CO_2 equivalent (Mt CO_2e). Furthermore, a more ambitious timetable for decarbonization promises to make Germany – Europe's largest GHG emitter and largest economy – a lead market for climate protection technologies. This, in turn, would create tremendous export potential for German industry.

In order to achieve the goal of climate neutrality by 2045, this study identifies specific opportunities for further accelerating the energy transition. In particular, it will be necessary to speed up the development of the hydrogen economy, the expansion of renewable energy, and the transformation of transport and agriculture, while also expediting the development of carbon capture and sequestration. In general, technologies available in the market today or by 2030 will scale more rapidly from 2030 onwards. Our 2045 scenario thus has a technology focus – in part because researchers today anticipate limitations in the improvement of energy efficiency.

"Climate-Neutral Germany 2045" shows that an accelerated and comprehensive deployment of climate-friendly technologies in combination with a strong climate policy will ensure that Germany can achieve a climate-neutral economy as early as 2045 and contribute to international climate action through net negative emissions starting in 2045. To make this a reality, it is not necessary to adjust the technology paths for zero emissions by 2050. Rather, the transformation of the energy system must occur faster. In particular, it will be necessary to accelerate the timetable for replacing certain machines and plants.

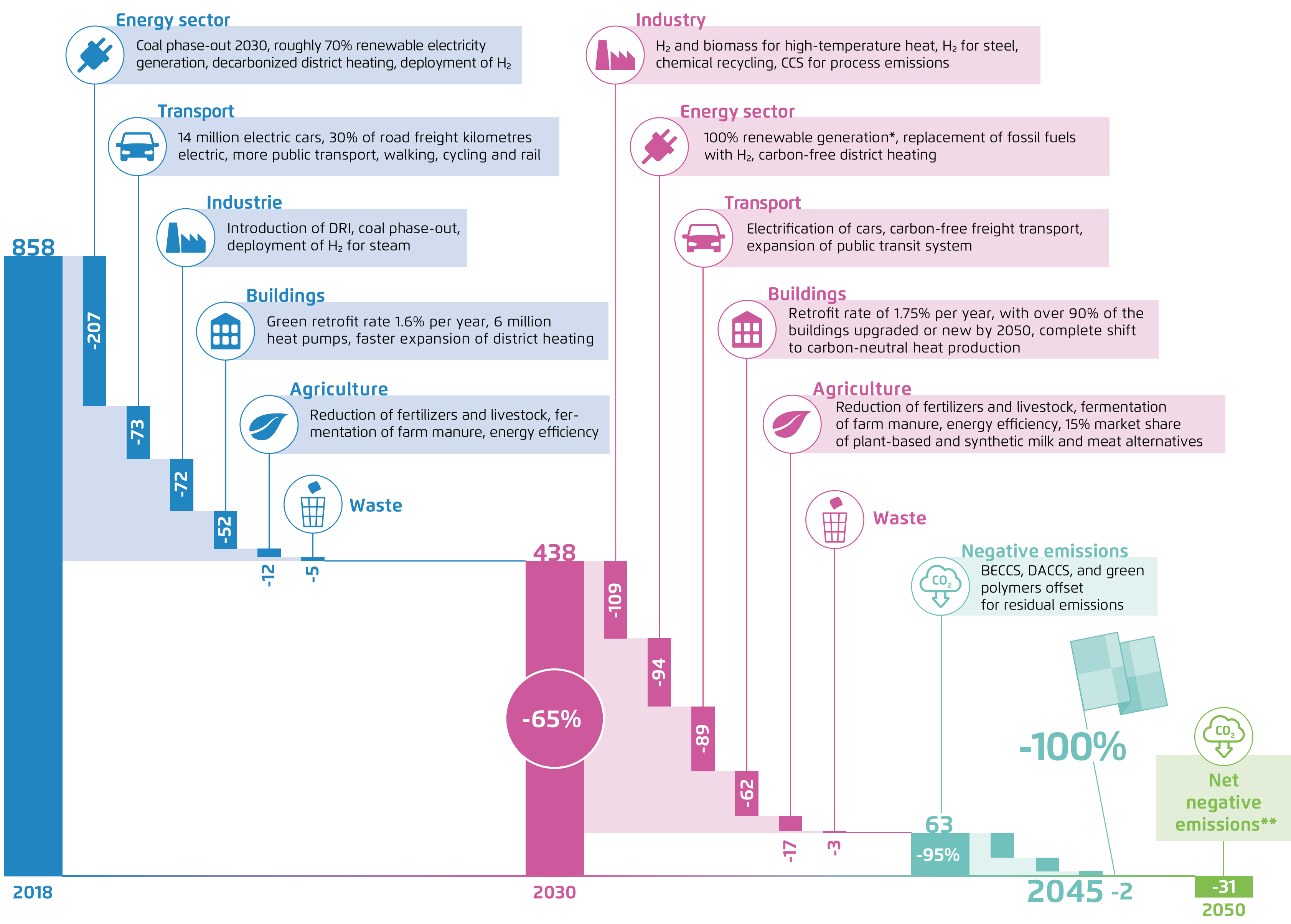
Our 2045 scenario does not foresee any additional behavioural changes in the form of restrictions to consumption. However, we do presume that certain changes to consumer demand already discernible today will gain momentum, including significant and growing market shares for meat and dairy alternatives and synthetic meat. Climate neutrality by 2045 can be achieved while maintaining the underlying conditions for demographic and economic development in Germany.

In an accelerated transformation scenario, the feasibility and cost-effectiveness of policy measures become particularly important. Accordingly, we reevaluated the measures identified in the original 2050 scenario, specifically with a view to faster implementation after 2030. When selecting measures for the 2045 scenario, economic efficiency remained our primary objective. Measures with lower CO_2 avoidance costs were generally given preferential status. Due to the need for faster transformation, the question of technical feasibility and associated market penetration rates received even greater attention. We primarily considered technologies with low technical and economic risks, and we minimized additional reliance on CCS for faster target achievement. Whenever possible, we put a preference on alternative technologies.

Our 2045 scenario takes into account greenhouse gas emissions in all sectors. We retained the original scenario's sector categories (energy, transport, industry, buildings, agriculture, waste, and land use) while preserving the same level of data granularity to ensure comparability between findings.

Measures for the climate-neutral 2045 scenario (CN2045)
(Greenhouse gas emissions in Mt CO_2e)

Figure ES



H₂ = Hydrogen
* This includes electricity generated from renewably generated hydrogen,
** This figure merely extrapolates the trend after 2045; further emissions reductions are possible.

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1 Summary

Ambitious climate policy until 2030 is imperative for climate neutrality by 2045

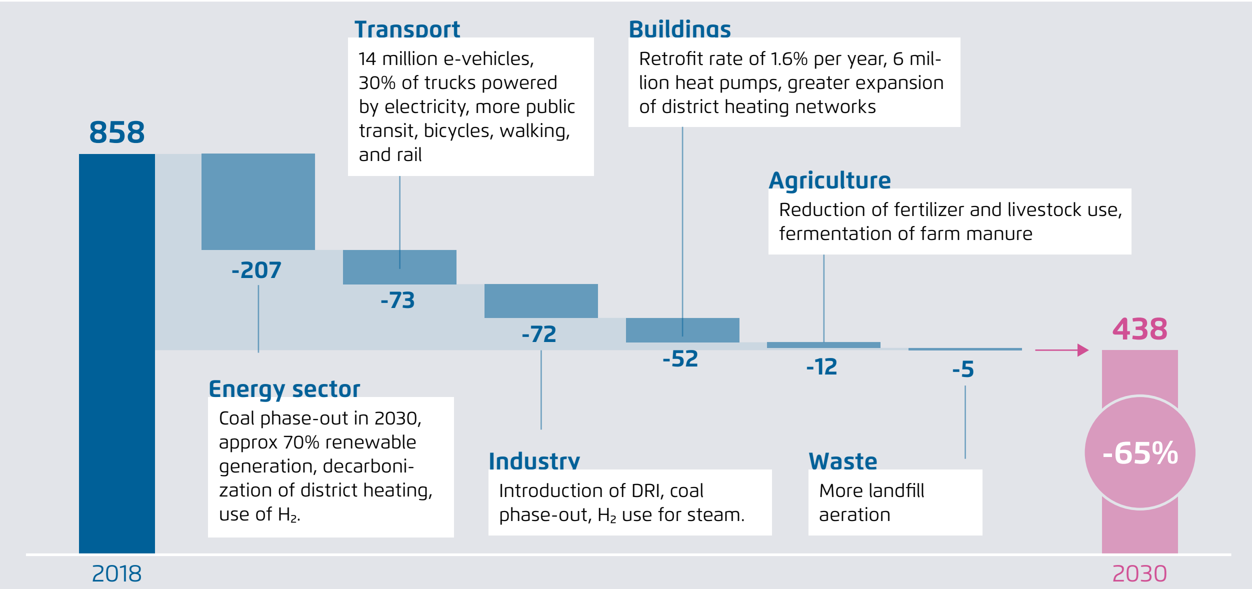
"Climate-Neutral Germany 2050" showed that reducing greenhouse gas emissions by 65 per cent in relation to 1990 is an ambitious but achievable interim target for 2030 on Germany's path to climate neutrality. "Climate-Neutral Germany 2045" retains the original study's focus on the factors and trends necessary to achieve the 2030 target.

As described in the previous study, existing climate regulations under Germany's Climate Protection Act (Klimaschutzgesetz) provide a good basis for additional emission reductions – but they must be significantly enhanced to achieve a 65 per cent reduction by 2030. Based on our review of the calculations performed for the 2050 study, additional emission reductions in the areas of agriculture and waste will be nearly impossible. Furthermore, in the transport and building sectors, only 5 million tons of additional reductions appear feasible in each. By contrast, we believe that it is possible to attain larger additional savings in the industry and energy sectors – 17 and 77 Mt CO_2e, respectively.

Overall, the measures listed below, which go beyond the existing climate regulations, would lead to the avoidance of 420 Mt CO_2e greenhouse gases in Germany between 2018 and 2030.

Three steps to climate neutrality: Step 1 – 65% reduction by 2030 (Greenhouse gas emissions in Mt CO_2e)

Figure 1



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Note: H_2 = Hydrogen

By 2030, the **energy sector** can reduce emissions by 207 Mt CO_2e. Compared with the target for the sector established by the Climate Protection Act, the additional savings amount to 77 Mt CO_2e. These additional savings are based primarily on a coal phase-out by 2030 in combination with expanded power generation from renewables. In addition, beginning at the end of the 2020s, hydrogen will be increasingly used in power plants and combined heat and power (CHP) plants. We assume that an earlier coal phase-out will occur after the EU tightens its reduction target to 55 per cent and adjusts the EU Emissions Trading System. Higher CO_2 allowance prices will accelerate the phase-out of coal-fired power generation.

With increasing electrification in all sectors, electricity consumption will rise 9 per cent between 2018 and 2030 (for an absolute increase of 51 TWh). Renewable energy will cover around 70 per cent of gross electricity demand in 2030. To enable this renewables share in the power mix, offshore wind power will be expanded to 25 GW, onshore wind power to 80 GW, and photovoltaics (PV) to 150 GW.

In the **industry sector**, new and more efficient techniques for processing industrial materials will be established. The transformation will be aided by the fact that 50% of the German industrial facilities in the basic commodities industry are due for replacement in the next ten years. The steel industry could be a pioneer in the field. Blast furnaces that are coming to the end of their service life can be replaced by direct reduction plants that run primarily on hydrogen and partially supplemented by natural gas (and eventually biomass).

Other industrial subsectors will also need to invest in yet-to-be-developed technologies based on electricity or hydrogen (particularly green H_2). This will mean investing in the necessary infrastructure to supply hydrogen to industry and to enable large-scale carbon capture and storage (CCS), not only in the cement and lime industries, but also in steel and chemicals (for bioenergy with CCS, or BECCS). Equally important will be early investment in circular material flows, including higher shares of secondary raw materials, so that these solutions can reach their full potential in the 2030s. The first CCS plants in the cement industry could be in operation as early as 2030.

Additional reductions in the **buildings sector** will be achieved by 2030 through changes in the composition of energy sources used in heating, the expansion of district and local heating grids, and more rapidly retrofitting the building stock (a 50% increase over the 2015 rate). Heat pumps will need to achieve large market shares in the installation of new heating systems by the mid-2020s, especially in the area of single-family homes and duplexes.

In our 2045 scenario, six million heat pumps will be in use by 2030. In urban areas, green district heating will gain increasing importance. After 2025, it will be necessary to limit the installation of new heating systems based on fuel oil or natural gas to exceptional cases.

In the **transport sector**, transformative changes will need to occur by 2030. In our 2045 scenario, personal mobility does not suffer restrictions. Instead, people become more reliant on sustainable modes of transport, including public transit, bicycles, and walking. By 2030, Germany's vehicle fleet will already contain 14 million electric cars (including plug-in hybrids). Goods will be increasingly transported by rail, and trucks that run on batteries, overhead lines, and fuel cells will cover nearly one-third of road freight mileage.

In the **agricultural sector**, implementing available technical mitigation measures remains the primary focus until 2030. Examples include the fermentation and improved storage of farm manure and the use of low-emission slurry and manure-spreading technologies. At the same time, further reductions will be achieved through changes in agricultural production. These include expanding organic farming, switching to crops with lower nitrogen requirements, and reducing livestock numbers. These changes in production will follow changes in demand: in line with current trends, fewer animal products will be consumed, and in the area of bio-energy, there will be a shift from gaseous to solid biofuels.

In the **waste sector**, methane emissions from landfills will decrease between 2018 and 2030. The expansion of landfill aeration will further accelerate the reduction of methane emissions. Other areas of the waste sector have only small reduction potentials in this period.

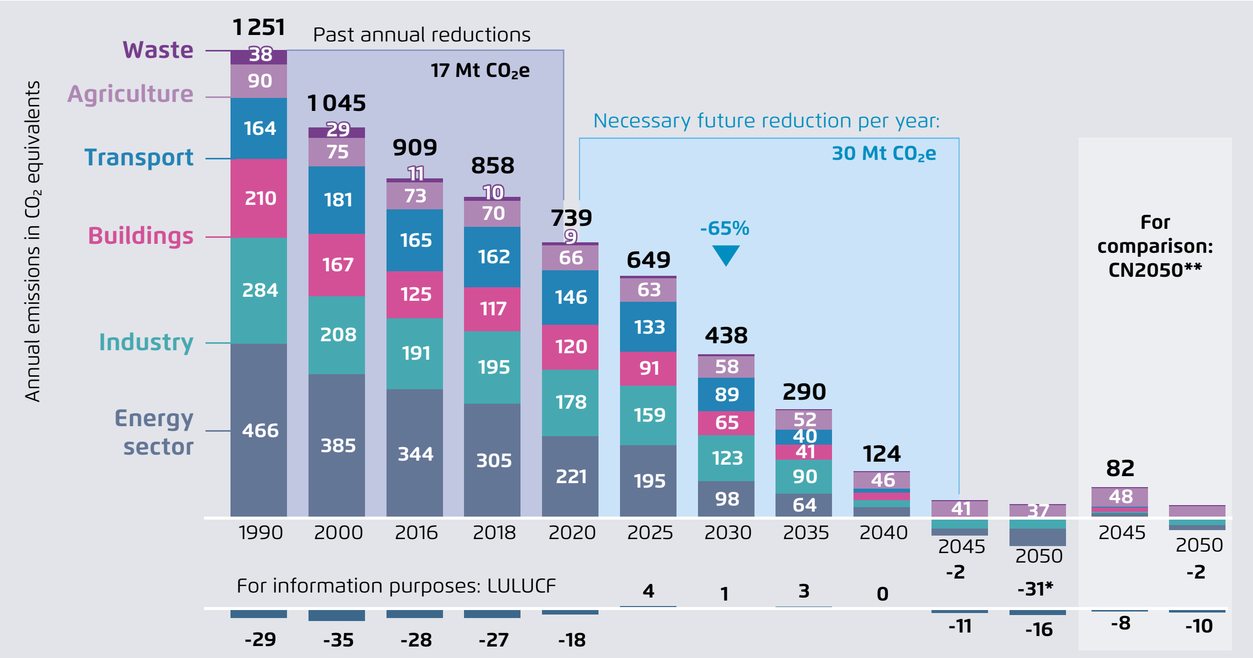
Net zero by 2045 – accelerating progress to a 95 per cent reduction in emissions

With the measures presented in this study, two-thirds of the necessary GHG reductions needed to reach climate neutrality can be achieved by 2030. To abate the remaining third, however, it will be necessary to remain firmly committed to the decarbonization project. "Climate-Neutral Germany 2050" assumes a 20-year period for completing the journey to net zero; the 2045 scenario shortens the time window by 25 per cent. This means an accelerated timetable for policy implementation, technology development and deployment, and infrastructure investment.

By intensifying efforts in all of these areas, Germany can achieve carbon-neutrality as early as 2043 and climate-neutrality by 2045. If the trends described

Overview of GHG emissions by sector

Figure 2



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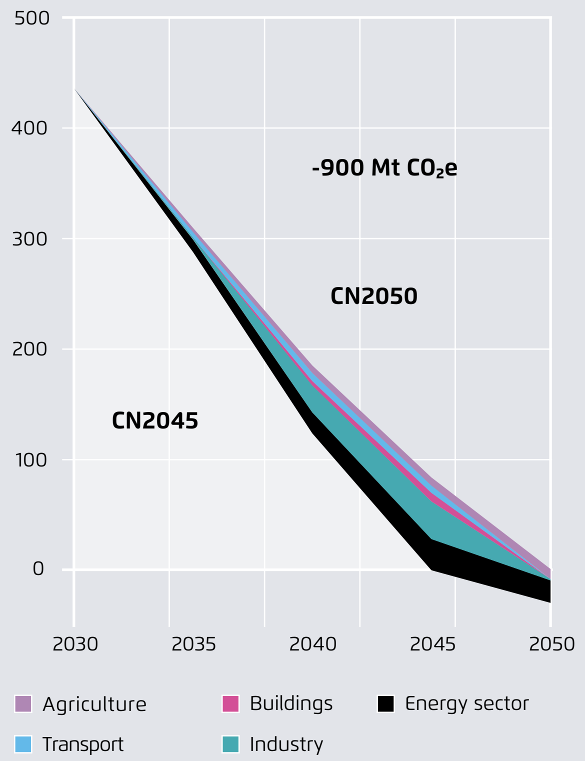
Negative emissions are considered in the sectors directly.
* This figure merely extrapolates the trend after 2045; further emissions reductions are possible.
** Climate-Neutral Germany 2050

Additional GHG savings and measures by sector — Figure 3

Additional reductions of GHG emissions between the CN2050 and CN2045 scenarios in Mt CO_2e



Measures for reaching climate-neutrality by 2045

-104 Mt
- Reduced livestock due to higher demand for milk and meat substitutes
- Accelerate expansion of organic farming to 25% of farms
- Expansion of peatland rewetting and increase of biodiversity areas

-73 Mt
- No permitting of new combustion engine cars or plug-ins from 2032 onwards
- Fleet of cars and trucks in 2045 almost completely free of combustion engines
- PtX for inland waterway transport already from 2031

-68 Mt
- Accelerate expansion of heat pumps and district heating networks
- Replace all fossil heating technologies by 2045
- Increase building retrofit rate to 1.75%

-308 Mt
- Accelerate expansion of CCS infrastructure
- Accelerate availability of biomass for BECCS
- Accelerate shift of energy source to electricity and hydrogen

-345 Mt
- Accelerate and increase renewable expansion starting in 2030
- Increase negative emissions through DACCS
- Accelerate replacement of natural gas with hydrogen
- Increase inland hydrogen production

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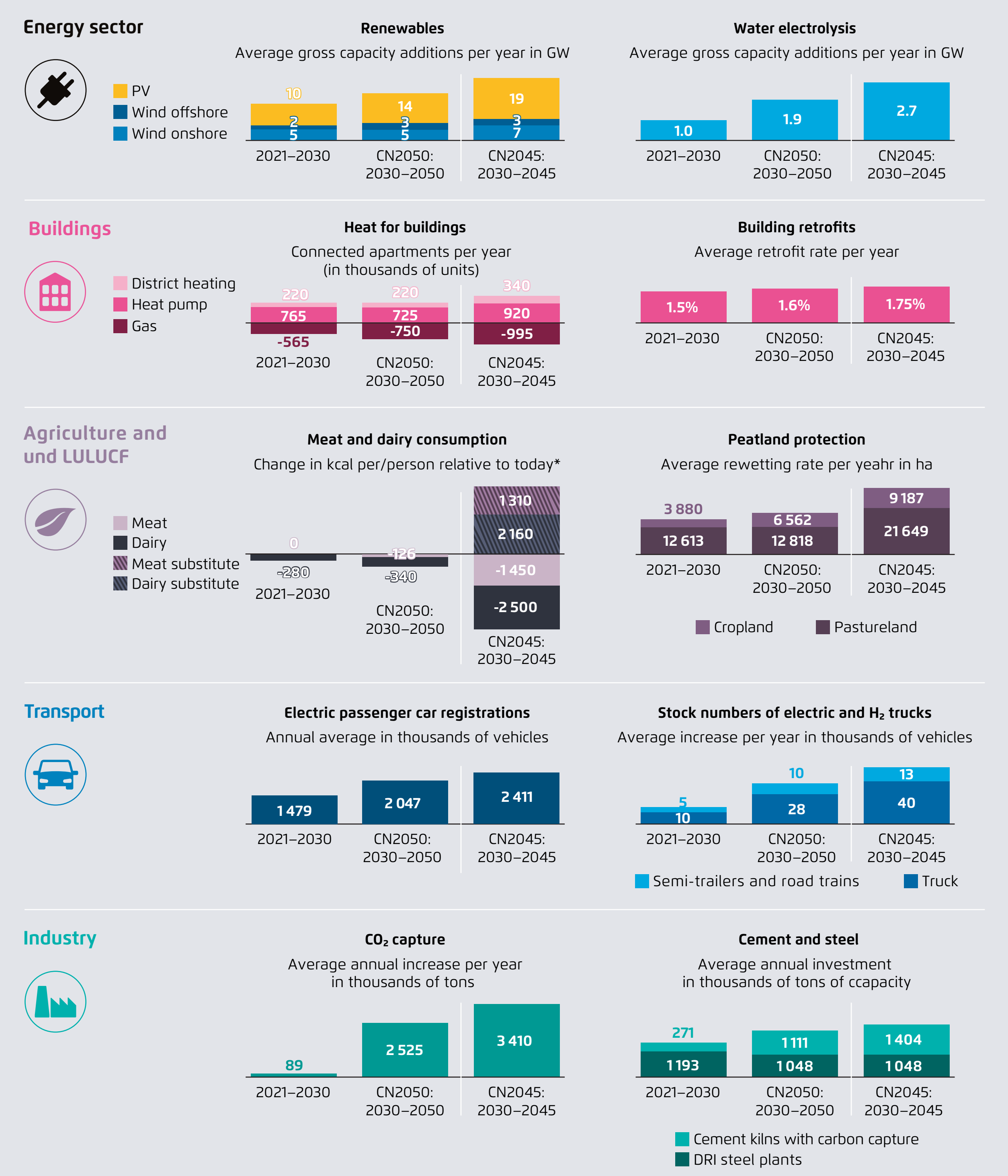
in this study continue beyond 2045, Germany will eventually reach net negative emissions that could offset positive emissions elsewhere, thus contributing to global climate efforts.

In our climate-neutral scenario for 2045, electrification occurs faster and hydrogen gains importance as an energy source and feedstock sooner than in "Climate-Neutral Germany 2050". At the same time, the accelerated timetable intensifies the pressure on all sectors to achieve energy-efficiency improvements. However, supply-side measures are easier to accelerate than demand-side efficiency measures. This will lead to faster and greater growth in power demand. Carbon capture and storage (CCS) will also need to play a larger role. In the 2045 scenario, solid biomass remains just as important in sectors with process-related carbon flows and highly concentrated energy demand at sites suitable for CCS (especially steel and chemicals).

Implementation speed in the scenarios CN2050 and CN2045 Figure 4



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* Today, Germans consume around 900 kcal/day/person in meat and dairy products. In 2045, the share of substitute products will make up around 15% of meat and dairy consumption.
The 2030–2050 period relates to the CN2050 reference scenario

The following developments are necessary in individual sectors to accelerate the achievement of **climate neutrality from 2050 to 2045**:

→ Faster and increased deployment of renewable energy is needed in the **energy sector**. Electricity demand is forecast to increase by 60 per cent between 2030 to 2045, reaching 1 000 TWh, mainly due to electrification and increasing hydrogen production. Renewable energy expansion after 2030 remains focused on wind energy and PV. Hydrogen will become increasingly important, and will replace natural gas as the most important energy source for residual power generation after 2040. The production of electricity and district heating will be completely carbon free by 2045. Compared to the original 2050 study, gross electricity consumption is 130 TWh higher in 2045, and 40 TWh higher in 2050. This increased electricity consumption is attributable to the faster electrification of other sectors, as well as higher hydrogen demand, which is partially covered by domestic production (in order to limit imports). In addition, the accelerated timetable for decarbonization means less progress can be completed in improving energy efficiency in various areas of application by the target year of 2045. Our 2045 scenario explicitly relies on the accelerated ramp-up of climate protection technologies on the supply side, because we have not presumed more rapid efficiency gains, or restrictions to demand.

  Accordingly, in order to meet the electricity demand that would be associated with climate neutrality by 2045, more rapid expansion of wind and PV is required after 2030. In total, 385 GW of installed PV capacity would be necessary in 2045, a 70 GW jump over the original 2050 scenario. More robust expansion trends would also be necessary for wind power. By 2045, there will need to be on- and offshore wind capacity of 145 and 70 GW, respectively. Compared with the original 2050 scenario, this means 17 GW of supplemental onshore capacity and 9 GW of supplemental offshore capacity in 2045. The acceleration poses a major challenge, particularly for offshore wind development, which has extremely long planning periods. In addition, the increase in onshore wind and PV means higher land use requirements.

→ The **industrial sector** can become nearly climate-neutral by 2040 given increasing reliance on electricity, hydrogen, and – to a lesser extent – biomass. Starting as early as 2030, chemical feedstocks will gradually be replaced by chemical recycling and synthetic inputs based on green energy feedstocks without fossil carbon.

  Compared with the original 2050 scenario, biomass will be used sooner to meet the large-volume heating needs of industry. Furthermore, the CO_2 grid will be expanded at a faster rate from 2035 on, and will be completed by 2045. Industrial carbon producers with an annual capture volume of 30 million metric tons will be connected to the grid between 2030 and 2040, and the annual injection volume will increase to 52 million metric tons by 2045.

  The 2045 scenario does not take into account other options that could lead to more rapid emission reductions. In the industrial sector, for example, emissions could fall faster prior to 2040 given the decreased production of energy-intensive goods due to falling demand. Slower construction activity could lower demand for cement and steel, and more durable products would reduce the demand for plastics.

→ In the **buildings secto**r, our 2045 scenario presumes faster energy retrofit rates and lower demand for new construction starting in 2030. The share of the housing stock receiving an energy retrofit has been revised upward to nearly 1.75 per cent annually between 2030–2045. This is slightly higher than the 1.6 per cent retrofit rate presumed between 2030 and 2050 in the original climate-neutral scenario for 2050. Thanks to the higher retrofit rate, over 90 per cent of commercial and residential units will undergo energy retrofitting between 2000 and 2050. At the same time, for the period after 2030, our 2045 scenario slightly accelerates the energy efficiency gains witnessed when refurbishing the existing building stock. The scenario also foresees rapid improvements to construction efficiency standards.

After 2025, new heating systems that rely on fossil fuels will be installed only in exceptional cases. (In this regard, the 2045 and 2050 scenarios are identical.) In the current scenario, the operating life of fossil-based heating system is limited to 20 years. Compared with the 2050 scenario (which presumes longer operational lifespans for some heating systems), this 20-year restriction does not lead to a significant divergence in practical natural gas heating lifespans, as the phase-out of such heating units will be encouraged by market effects. Due to the strong decline in natural gas heating systems in the buildings sector, the cost of operating and maintaining gas distribution grids will be borne by ever fewer end customers. For the remaining customer base, this effect will increasingly disincentivize natural gas use. Furthermore, when the customer base drops below a critical threshold in a given grid area, decommissioning of the entire grid can be expected. As grid fees rise, grid disconnections accelerate, and entire subnetworks shut down, leading to the abrupt loss of many customers. Different areas of the grid experience this pattern at different times. As a result, cumulative nationwide figures track a smooth downward curve. Some local distribution grids may persist longer due to the switch to biomethane.

By 2045, these trends will lead to the replacement of most fossil-based heating units. At the same time, the progressive development of green heating systems and the expansion of district and local heating grids will all but eliminate carbon emissions from the buildings sector, with the exception of a residual amount of 3 Mt CO_2e. By 2050, only low methane and nitrous oxide emissions from biomass will persist. Between 2030 and 2045, an annual average of 920 000 residential units will be connected to heat pumps. This will increase the total number of heat pumps to 14 million by 2045 (a figure not reached until 2050 in the original scenario).

Reduction options based on behavioural changes that deviate from current trends were not considered in this study. Per capita living space, for example, has increased significantly in recent years, and such an increase is also assumed in the current scenario.

→ In the **transport sector**, our study assumes that per capita mileage in passenger transport will remain at about the same level, while freight transport is projected to rise due to economic growth. Changes are foreseen mainly in terms of the speed of electrification.

Beginning in 2032, no new passenger cars with combustion engines will be registered. By 2045, the national vehicle fleet will consist almost exclusively of electric cars. A residual stock of classic cars older than 30 years will remain on the road, however. In 2045, road freight, buses, and rail will be almost entirely electrified (battery electric, overhead lines) or powered by fuel cells. Compared with the original scenario for 2050, we assumed an accelerated deployment of synthetic fuels. In 2035, for example, 20 per cent of the final energy demand for inland waterway transport will be covered by synfuels, and this figure will climb to 100 per cent by 2040. We presume that the share of power fuels in air and waterway transport will increase significantly from 2035 onwards, and will reach 100 per cent by 2045. In relation to our 2050 scenario, the higher cost of synfuels, combined with other measures, will slow growth in international air transport demand.

→ In the **agricultural sector**, significant emissions reductions will be achieved by 2045 through the conversion of livestock and the fermentation of a large share of farm manure in biogas plants. The most important change relative to the 2050 scenario is the higher demand for plant-based and synthetic meat and milk substitutes. These substitutes will capture a 15 per cent market share by 2045. As the market for dairy and meat substitutes is already witnessing dynamic growth (albeit from a low starting point), a 15 per cent market share by 2045 represents a mid-range estimate. It can be assumed that manufacturers will continue to improve the flavour of such products and that technical advancements, economies of scale, and competitive pressures will further reduce prices. Over the long term, it should be possible to offer substitute products at lower market prices than natural products. This will have attendant effects on German meat and milk exports. Substituting 15 per cent of meat and dairy products with plant-based alternatives will reduce livestock inventories and associated emissions.

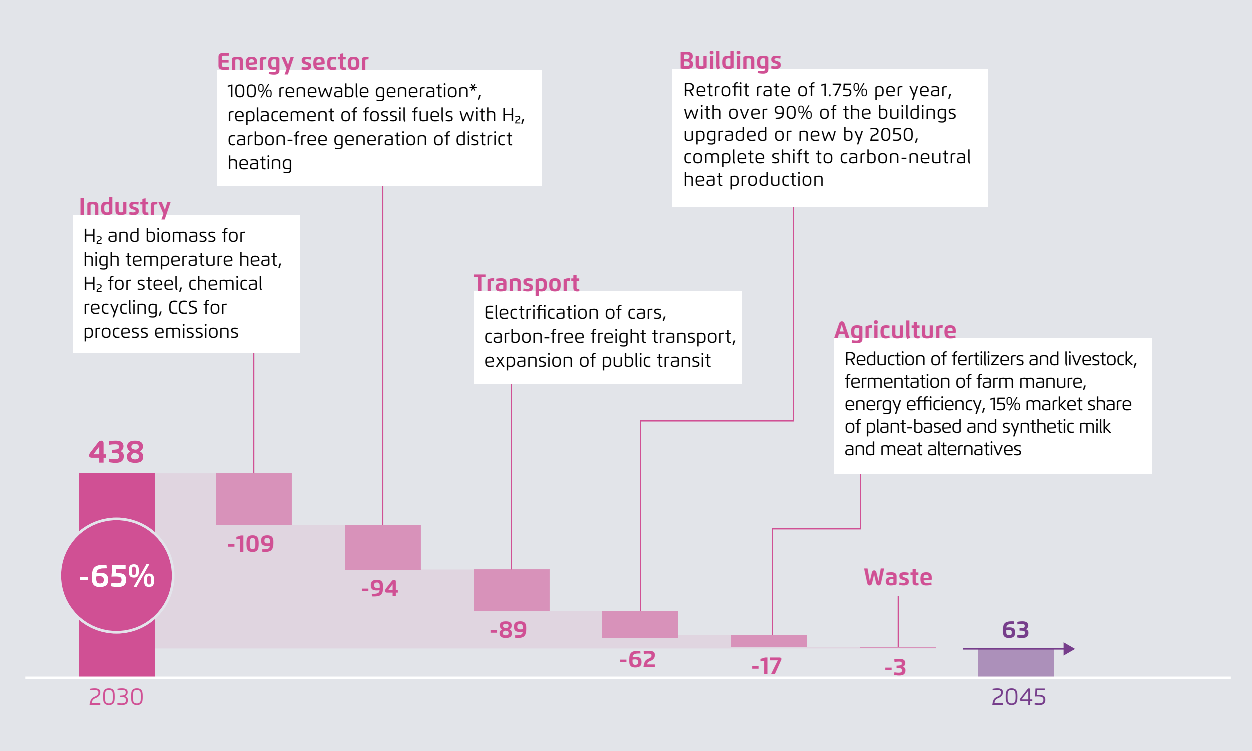
In the area of agricultural soils, both the 2050 and 2045 scenarios assume that the industry will tap the sector's substantial emissions reduction potential by 2030. For the period after 2030, the 2045 scenario takes additional soil-related abatement effects into account. For greenhouse gas neutrality by 2045, abatement measures must be implemented earlier, or more quickly after 2030. In particular, these measures include peatland rewetting, the expansion of organic farming, and increases to non-productive land. The 2045 scenario also assumes a more rapid and expanded development of short-rotation plantations and commercial woodland. In the agricultural sector, an additional effect of an accelerated timetable for climate neutrality is a greater industrial demand for wood fuel. Relative to the original scenario for 2050, our 2045 scenario requires a larger volume of land to be dedicated to biomass production. This land will become available in a timely manner due to declining livestock populations, which will reduce demand for grazing land.

→ In the **waste sector**, residual emissions from landfills, biological treatment, and wastewater treatment will persist in 2045. Due to biological processes, emissions from the waste sector cannot be completely avoided. Reductions will be achieved in all areas by 2045, however.

Compared with the 2050 scenario, landfill aeration projects in the waste sector will undergo an expedited expansion between 2030 and 2040.

Step 2 – 95% reduction without negative emissions
(GHG emissions in Mt CO_2e)

Figure 5



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* This includes power generation from renewable hydrogen as well as stored and imported renewable electricity.

Offsetting unavoidable residual emissions with CCS and negative emissions

Residual GHG emissions are those that cannot be further reduced by abatement measures. They arise primarily in the agricultural sector from animal husbandry and the use of fertilizers. Residual emissions also occur from industrial processes and waste management. Energy-related greenhouse gas emissions, by contrast, can be avoided through the use of renewable energy (except for very low methane and nitrous oxide emissions from the storage, transport, and combustion of biomass and synthetic fuels). Across all sectors, residual emissions of 63 Mt CO_2e will remain in 2045 – equivalent to five per cent of 1990 emissions.

As in the climate-neutral 2050 scenario, these residual emissions will be offset with special technologies that directly or indirectly remove CO_2 from the atmosphere and store them for the long term:

→ Bioenergy with Carbon Capture and Storage (BECCS) refers to the capture and geological storage of CO_2 produced by the combustion of biomass. Since biomass is largely CO_2-neutral when grown sustainably and used as a residual fuel, BECCS removes CO_2 from the atmosphere in the long term. BECCS use will focus on the industrial sector due to the limited amount of sustainable biomass available.

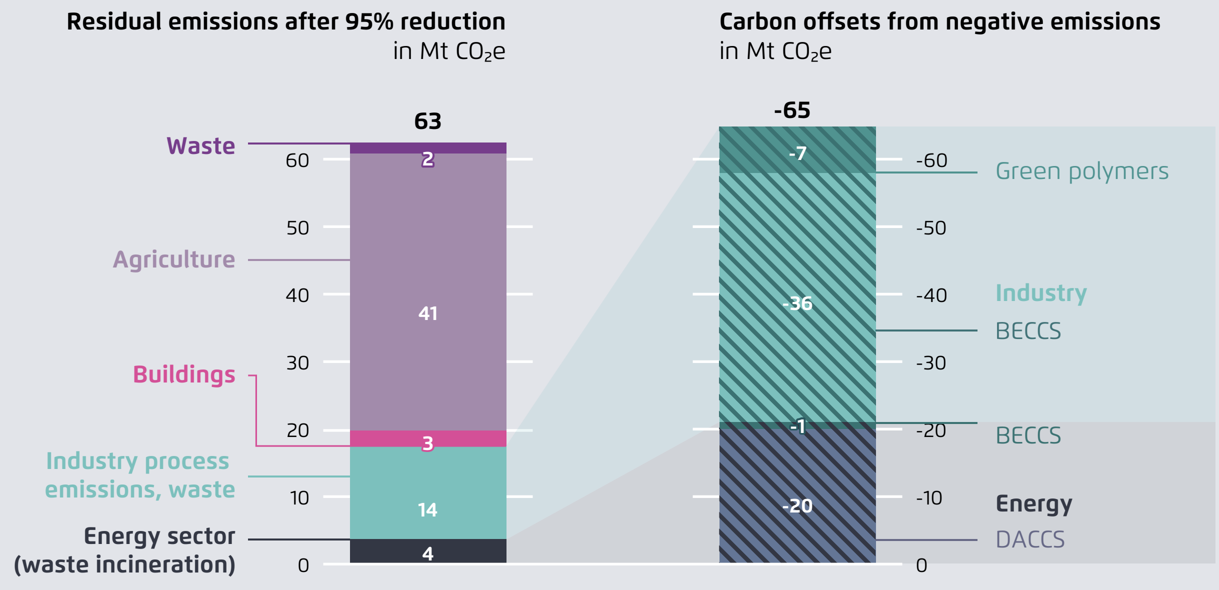
→ Direct Air Carbon Capture and Storage (DACCS) refers to direct CO_2 capture from the air and subsequent storage in suitable geological formations. DACCS is associated with significantly higher energy requirements and costs than BECCS.

→ Green feedstocks/material binding of CO_2 in green polymers: Green naphtha and other hydrocarbon materials are produced with CO_2 captured from the air or from biomass. This base material is produced using the Fischer-Tropsch synthesis, with green hydrogen as an input. These are then further processed into green plastics, which can be kept in the material cycle on a permanent basis, provided that there are improvements to the recycling system. When combined with CCS in waste incineration, this can avoid the emission of carbon previously captured from the atmosphere.

As a result of the increased, expedited use of these technologies versus the original 2050 scenario, more CO_2 will be removed from the atmosphere than introduced as early as 2045, yielding net negative emissions. After 2045, residual emissions will continue to decline while direct air capture facilities continue to expand. This will result in Germany achieving net negative emissions of -30 Mt CO_2e in 2050.

As a supplement to these technical measures, an additional modification will be the increased reliance on land use, land use change, and forestry measures (LULUCF) for the rewetting of peatlands. This will ensure that this sector remains a CO_2 sink over the long term. With an expansion of LULUCF measures, a sink of -11 Mt CO_2e will be achieved in 2045, and will increase to -16 Mt CO_2e by 2050. The current sink level (-27 Mt CO_2e) will not be maintainable, however. Natural sinks, i.e., forests and soils that absorb carbon, are only reported in this study for informational purposes, and are not counted towards achieving climate targets.

Step 3 in detail – residual GHG emissions and their offsetting in 2045 — Figure 6



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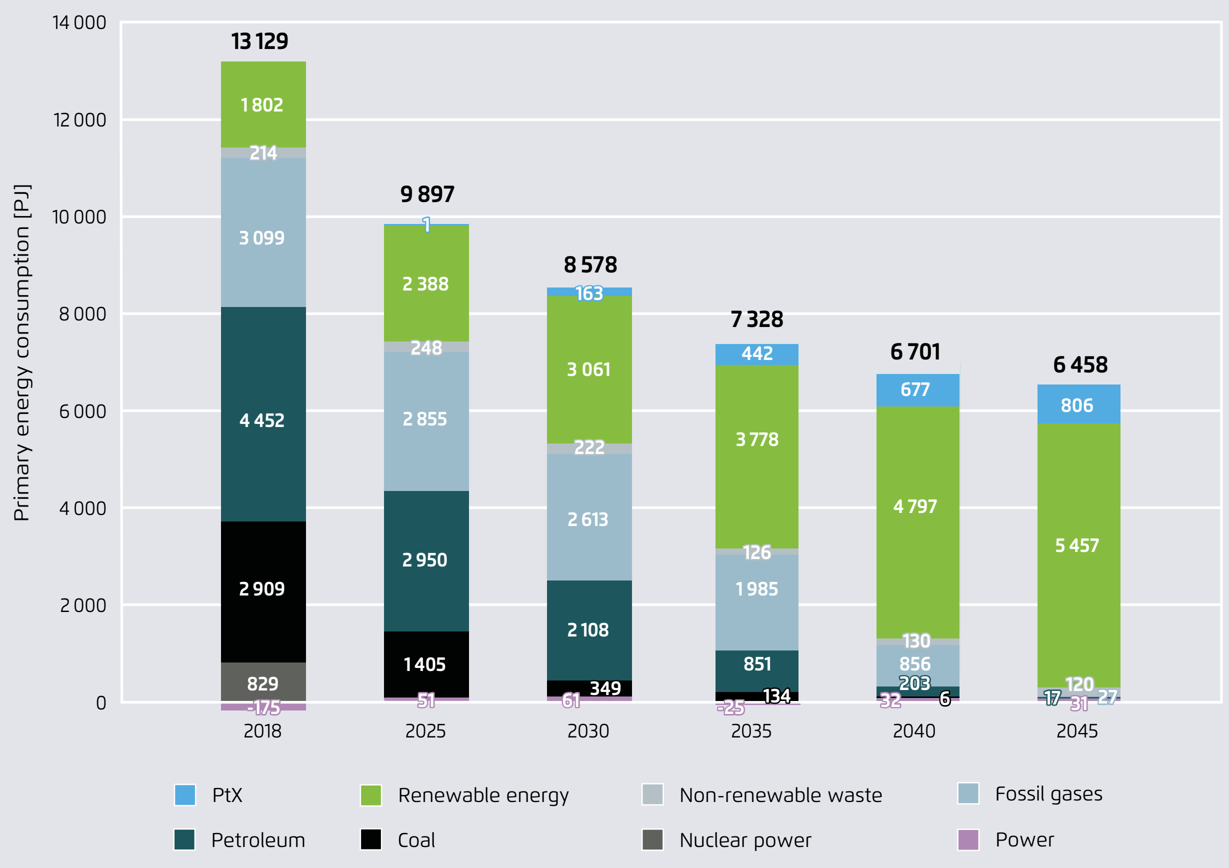
Three levers for acceleration: Lever 1 – Improve energy efficiency; reduce energy demand

In the climate-neutral 2050 scenario, Germany's primary energy consumption, i.e. the energy content of all energy sources used directly or for conversion into secondary energy sources, drops by 50 per cent between 2018 and 2050. Primary energy consumption declines from about 13 000 petajoules (PJ) today to about 6 500 PJ. In the current scenario, the halving of primary energy consumption is achieved in 2045. In both scenarios, this is the result of reduced losses in energy conversion, in combination with the significant decreases in final energy consumption. As the speed of transformation up to 2030 was not modified in the revised scenario, the decisive differences only become apparent after 2030.

Between 2030 and 2045, final energy consumption in the current calculations falls by a further quarter from 7 500 PJ to 5 750 PJ. This scale of reduction is not reached until 2050 in the original scenario. The key drivers of this faster decline are the accelerated and modified measures outlined in the aforementioned sectors, especially electrification.

Primary energy consumption

Figure 7



Prognos, Öko-Institut, Wuppertal Institut (2021)

Without international transport (aviation and shipping).

PtX products displace the fossil fuels still present in 2045 in the original 2050 scenario.

In the area of energy conversion, as well, the transformation will proceed faster after 2030 in the climate-neutral 2045 scenario. In the period up to 2045, further primary energy savings will occur, particularly as a result of a faster switch to electricity generation from renewables. The majority of electricity generation in 2045 will be from wind energy and PV, which do not have conversion losses.

The composition of primary energy consumption in the climate-neutral 2045 scenario will change faster than in the climate-neutral 2050 scenario. The share of renewables in primary energy consumption will rise from 36 per cent in 2030 to 85 per cent by 2045. Imports of synthetic fuels will account for about 12 per cent of demand in 2045, with other energy sources such as waste and small amounts of imported electricity accounting for the remaining 3 per cent of primary energy in 2045. In the climate-neutral 2050 scenario, a similar composition of primary energy consumption will not be achieved until 2050.

Three levers for acceleration: Lever 2 – Renewable power generation and electrification

Electricity will be the primary energy on the road to a climate-neutral future. It can be generated renewably and used very efficiently in many applications. In the transport and heating sectors in particular, it has clear advantages over internal combustion engines and conventional boilers.

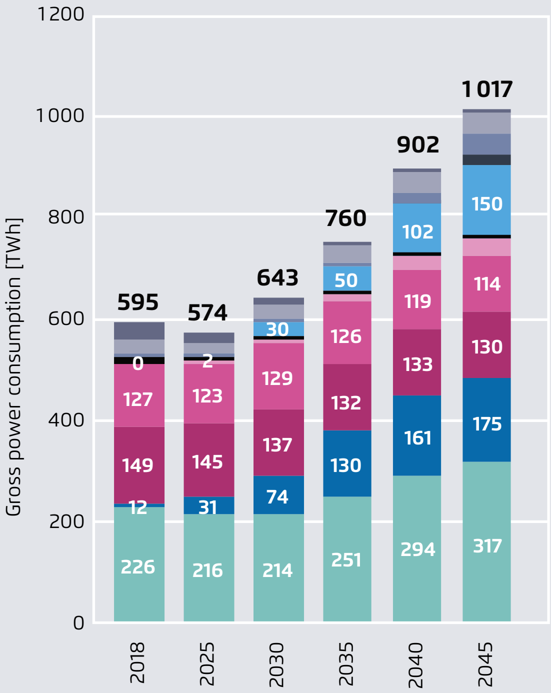
Compared with the climate-neutral scenario, electrification and the production of green hydrogen will increase faster, and fossil fuels will be replaced earlier. Electrification and hydrogen production will drive a significant increase in electricity consumption, reaching about 1 000 TWh by 2045. Electricity consumption in 2045 will then be around 400 TWh higher than today. Compared with the climate-neutral 2050 scenario, this represents an increase of around 130 TWh in 2045.

With regard to increased electricity consumption in 2045, some 160 TWh will be for transport, 150 TWh will be for hydrogen production, and about 90 TWh will be for industry. Electricity consumption in the buildings sector declines slightly in the 2045 scenario. Efficiency improvements in electrical appliances and lighting in combination with the replacement of storage heaters and electric boilers save more than heat pumps consume.

Power generation in Germany will be completely climate-neutral in 2045 – five years earlier than in the 2050 scenario – and the share of renewables in the power system will be 100 per cent. Renewable energy, including hydropower and biomass, will directly cover 89 per cent of electricity demand, while 6 per cent will come from gas-fired power plants that use hydrogen generated from renewables as fuel. The remaining 5 per cent will be covered by temporarily stored or imported electricity. By 2045, the power system will be very flexible and can operate efficiently even with a high share of fluctuating feed-in. This will be achieved through the faster expansion of battery storage and electricity trading with foreign countries. At the same time, electricity consumption will also be made more flexible via electric vehicles, heat pumps, and electrolyzers.

As in the climate-neutral 2050 scenario, battery storage, load management, and electricity trading serve to balance electricity demand and supply in the short term. Seasonal balancing is mainly achieved by generating and reconverting hydrogen and by using the large reservoir hydro power plants in Scandinavia and the Alps. Electricity exports to these countries can conserve storage levels – especially in summer and fall – and provide more electricity in winter.

Gross power consumption — **Figure 8**



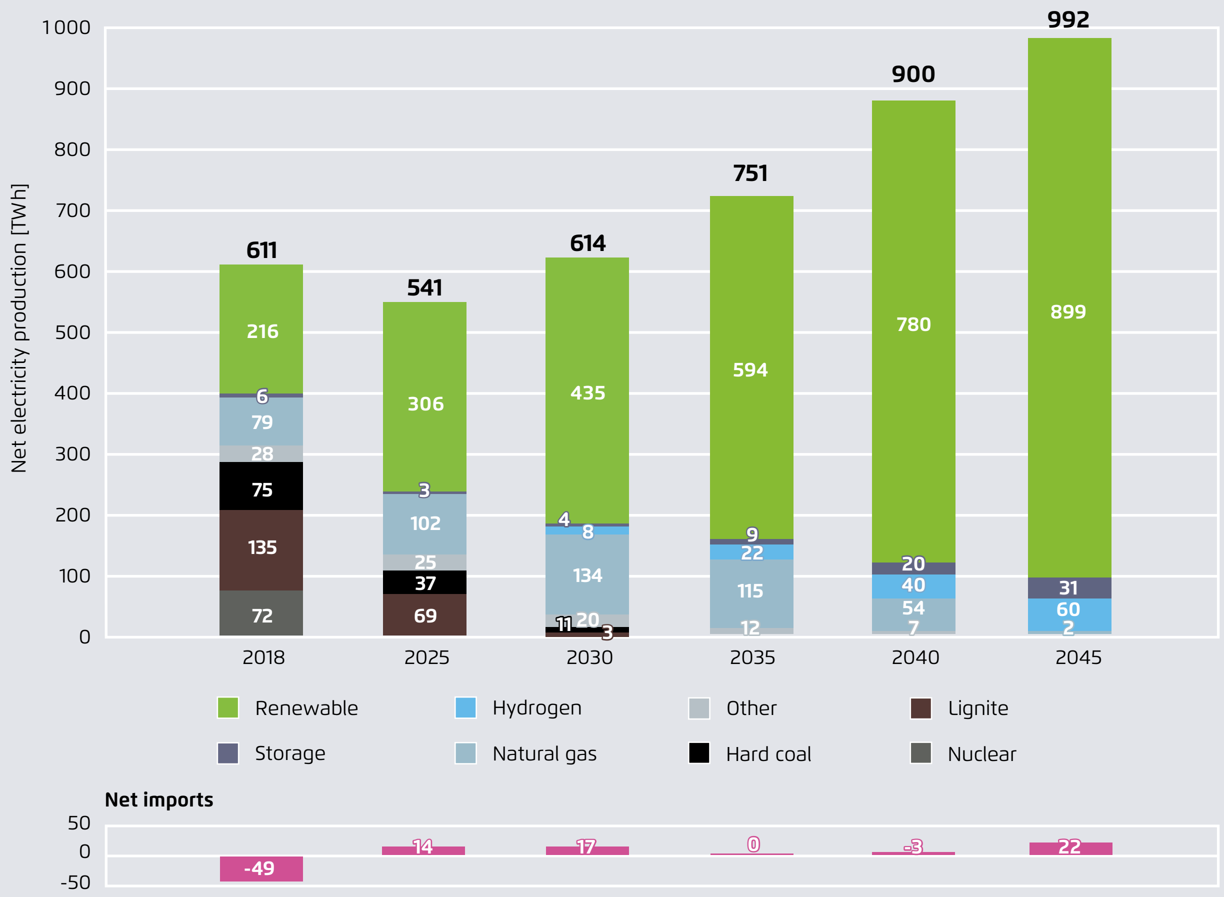
	2030	2045
H_2/CO_2	Production 19 TWh H_2	96 TWh H_2, 20 Mt CO_2 DAC
	5,6 million heat pumps, efficient electric appliances, efficient lighting, decline in direct electric heating	14 million heat pumps, increased use for cooling and ventilation, efficient heat pumps, decline of direct electric heating, efficient appliances
	Heat pumps, efficient lighting	Heat pumps, efficient lighting
	25% of vehicle kilometers travelled in road freight with batteries and overhead lines, 14 million electric cars	80% of vehicle kilometers travelled in road freight with batteries and overhead lines, 36 million electric vehicles
	Electrified process heat, electricity-based steam production, efficient cross-sectional technologies	Electrification of process heat, CO_2 capture, electricity-based steam production in electric boilers and high-temperature heat pumps

Prognos, Öko-Institut, Wuppertal Institut (2021)

DAC = Direct Air Capture, HH = Households, BTS = Business, trade and services.
Storage demand includes pumped storage hydro and stationary battery storage in public grids.
Power consumption of home batteries in combination with PV systems is not considered here.

Net electricity generation and import balance

Figure 9

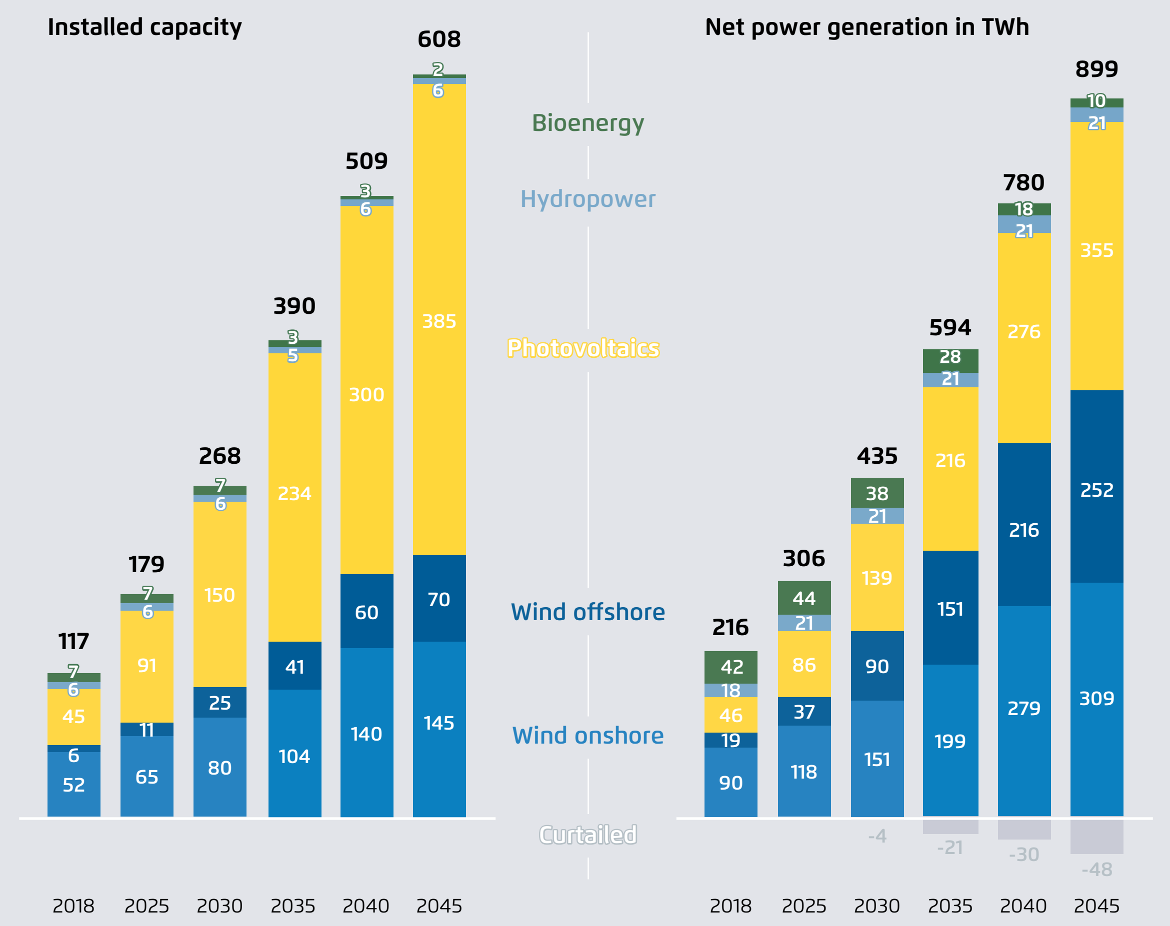


Prognos, Öko-Institut, Wuppertal Institut (2021)

Other producers: Dome gases, waste, petroleum, other

Renewable energy

Figure 10



Prognos, Öko-Institut, Wuppertal Institut (2021)

* This includes power generation from renewable hydrogen as well as stored and imported renewable electricity.

Three levers for acceleration: Lever 3 – Hydrogen as fuel and feedstock

In addition to electrification, an increased and early use of hydrogen compared with the climate-neutral 2050 scenario will enable climate neutrality more rapidly. In 2045, hydrogen demand will be 40 TWh higher than in the 2050 scenario, or 265 TWh in total. Some 36% of this hydrogen will be produced in Germany. The remaining hydrogen will be imported.

The areas of application for hydrogen are the same as those in the climate-neutral 2050 scenario. The largest share will go to electricity generation, in part via CHP plants. District heating networks that are fed with heat from CHP plants will rely in part on hydrogen. For cost reasons, hydrogen will not yet be used directly for space heating.

In the industrial sector, hydrogen will mainly be used for the direct reduction of iron ore for carbon-free steel production, as a raw material in basic chemicals, and for generating process steam.

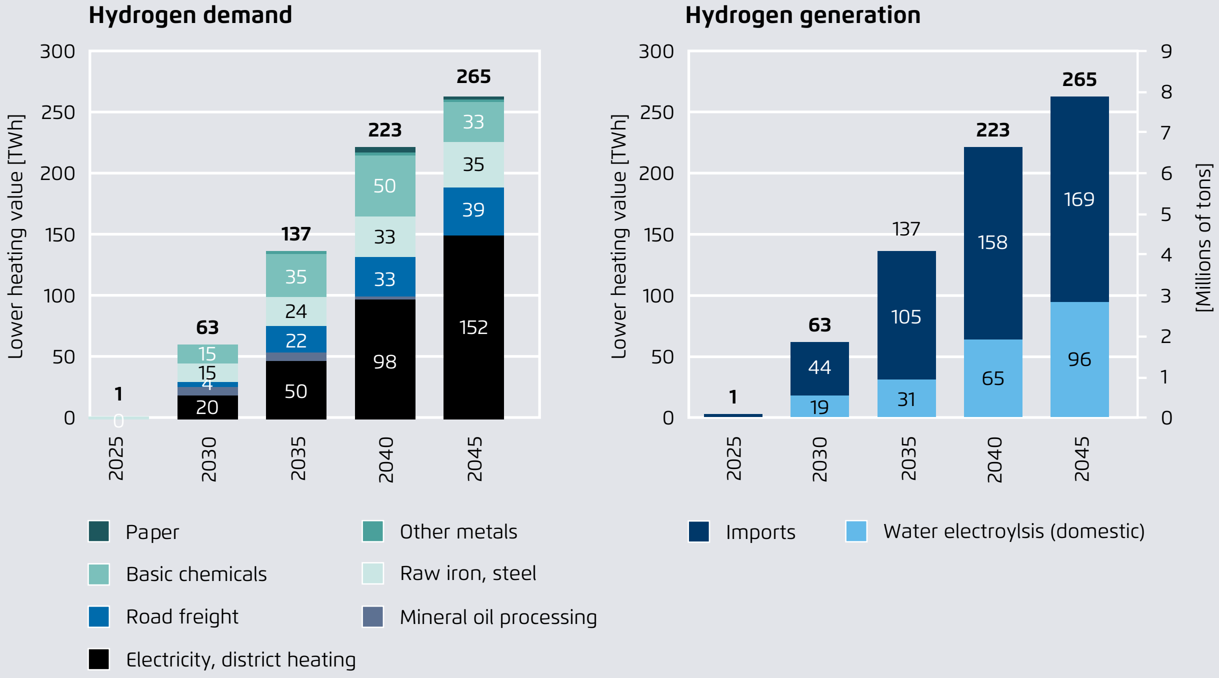
In transport, just under 40 TWh of hydrogen will be used, mainly in freight transport. Hydrogen will be predominantly used in the fuel cells of trucks and semi-trailers, and, to a much smaller extent, in light commercial vehicles.

In addition to hydrogen, other synthetic energy carriers are also used. CO_2-neutral power to liquid (PtL) fuels are mainly used in national and international shipping and aviation, and to a lesser extent in road transport, to power remaining vehicles with internal combustion engines. Green naphtha is used in industries when sufficient supplies of organic feedstocks cannot be provided by an increasingly circular economy. Power fuels and green naphtha are not produced in Germany but imported. Overall, they amount to 160 TWh.

The total demand for hydrogen and other synthetic fuels and feedstocks in 2045 is 427 TWh, of which 331 TWh are imported.

CO_2-free hydrogen generation and use in Germany

Figure 11



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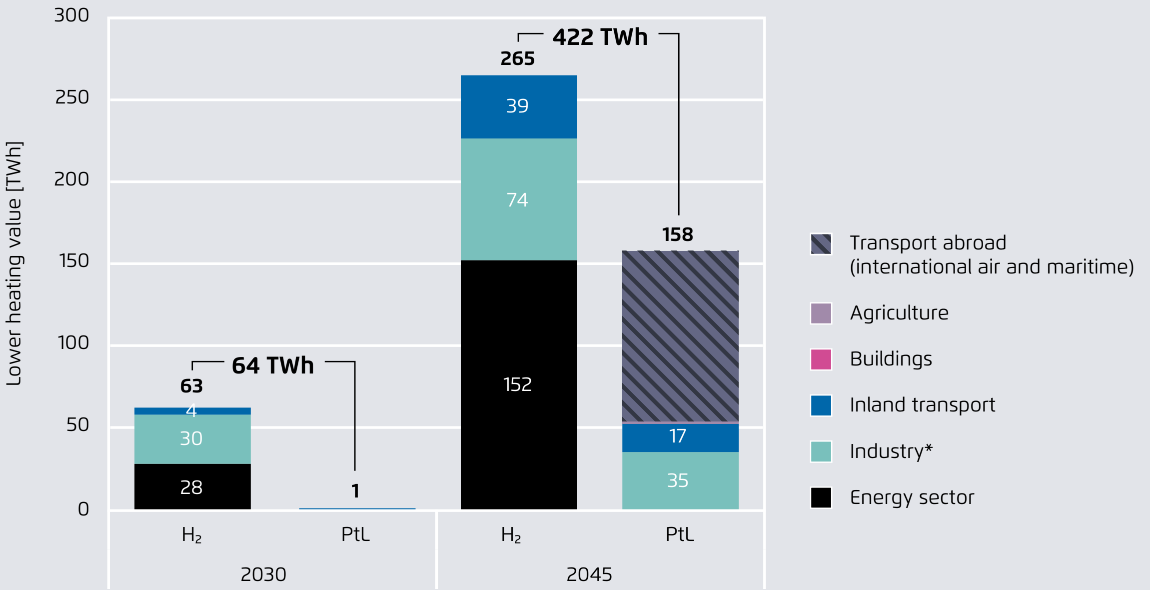
Excluding fossil hydrogen.

Hydrogen and PtL deployment

Figure 12



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* PtL-use in industry as feedstock (green naphtha and methanol).

Key indicators in the climate-neutral 2045 scenario

Figure 13

CN2045

		2018	2030	2040	2045	2018–2030 p. a. net	2030–2045 p. a. net
GHG emissions (Mt CO_2e)	Energy sector	305	98	26	-18	-17	-8
	Industry	195	123	19	-30	-6	-10
	Transport	162	89	11	0	-6	-6
	Buildings	117	65	19	3	-4	-4
	Agriculture	70	58	46	41	-1	-1
	Waste and other	10	5	3	2	0	0
	Sum	**858**	**438**	**124**	**-2**	**-35**	**-29**
	Reduction relative to 1990 (%)	31	65	90	100		
	LULUCF for informational purposes	-27	2	0	-11	2	0
	Primary energy consumption (PJ)	**13 129**	**8 578**	**7 328**	**6 458**	**-379**	**-141**
	Coal	*2 909*	*349*	*6*	*0*	-213	*-23*
	Mineral oils	*4 452*	*2 108*	*203*	*17*	-195	*-139*
	Fossil gases	*3 099*	*2 613*	*856*	*27*	-41	*-172*
	Gross power consumption (TWh)	**595**	**643**	**902**	**1 017**	**4**	**25**
	Renewable share of gross power consumption (%)	38	69	87	100**		
	Wind onshore (GW)	52	80	140	145	2	4
	Wind offshore (GW)	6	25	60	70	2	3
	Photovoltaics (GW)	45	150	300	385	9	16
	Number of electric vehicles (incl. plug-in hybrids; in millions of units)	0	14	32	36	1	1
	Freight transport rail (billions of km)	135	190	210	230	5	3
	Number of heat pumps (millions of units)	1	6	11	14	0,4	0,5
	Net energy demand for buildings (kWh/(m²·a))	106	85	69	57	-2	-2
	Electroylsis in Germany (GW)	0	10	37	50	1	3
	Use of hydrogen (TWh)	0	63	223	265	5	13
	Renewable hydrogen production in Germany (TWh)	0	19	65	96	2	5
	Imported hydrogen (TWh)	0	44	158	169	4	8
	Other imported synthetic fuels (TWh) – incl. international transport	0	1	57	158	0	10
	Carbon capture and storage (gross volume, Mt CO_2)	**0**	**-1**	-32	-73	0	-5
	Process emissions and waste (Mt CO_2)	*0*	*-1*	-11	-16	0	-1
	Negative emissions (Mt CO_2)	*0*	*0*	-22	-57	0	-4
	Negative emissions, incl. binding of materials (Mt CO_2)	**0**	**0**	-22	-65	0	-4
	Biomass CCS (BECCS, Mt CO_2)	*0*	*0*	-20	-37	0	-2
	Direct Act Capture CCS (DACCS, Mt CO_2)	*0*	*0*	-2	-20	0	-1
	Green polymers from imported feedstock (Mt CO_2)	*0*	*0*	0	-7	0	0
	Population in Germany (millions)	83	83	81	80	0	0
	EU-ETS, EUR 2019/t	16	52	70	80	3	2

Prognos, Öko-Institut, Wuppertal Institut (2021)

* Negative emissions are considered in the sectors directly.
** This includes power generation from renewable hydrogen as well as stored and imported renewable electricity.

Energy Balance Climate-Neutral Germany 2045 (in PJ)

Table 1

Sector	2018	2025	2030	2035	2040	2045
Total energy supply	**11802**	**9557**	**8330**	**7505**	**6799**	**6562**
Production (+)	4719	3563	3531	3926	4679	5244
Net Imports (±)	7520	6444	5254	3994	2512	1690
International aviation bunkers (–)	-393	-358	-363	-327	-310	-294
International marine bunkers (–)	-107	-92	-92	-87	-82	-76
Stock changes (±)	64	0	0	0	0	0
Statistical differences	**-84**	**0**	**0**	**0**	**0**	**0**
Statistical differences (±)	-84	0	0	0	0	0
Transformation processes	**-3426**	**-1852**	**-1386**	**-1253**	**-980**	**-1094**
Electricity, CHP & heat plants (±)	-2101	-964	-635	-624	-531	-460
Other transformation processes (±)	-587	-395	-348	-299	-170	-319
Own use and Losses (–)	-738	-492	-403	-330	-279	-314
Final consumption	**-8293**	**-7706**	**-6944**	**-6252**	**-5820**	**-5469**
Industry (–)	-2317	-2259	-2185	-2132	-2136	-2138
On-Road Transport (–)	-2203	-1911	-1482	-1073	-842	-702
Non-Road Transport (–)	-117	-119	-118	-125	-130	-129
Other: Commercial (–)	-1264	-1262	-1166	-1048	-951	-865
Other: Residential (–)	-2320	-2095	-1946	-1808	-1676	-1549
Non-energy use (–)*	-72	-60	-46	-66	-86	-85

Prognos, Öko-Institut, Wuppertal Institut (2021)

*only H_2 (fossil, PtH_2)

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How do we accomplish the clean-energy transition? Which legislation, initiatives and measures do we need to make it a success? **Agora Energiewende** and **Agora Verkehrswende** are helping Germany set the course towards a fully decarbonised energy system. As think-&-do-tanks, we work with key stakeholders to enhance the knowledge base and facilitate a convergence of views.

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