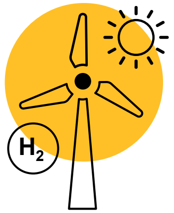
Institute of Energy Economics
at the University of Cologne

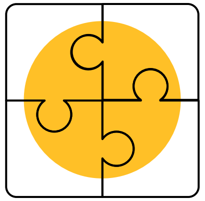
dena pilot study - Towards climate neutrality

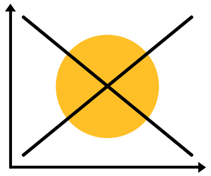
Climate neutrality 2045 - Transformation of the end-use sectors and the energy system

English summary (original German publication in October 2021)

On behalf of the German Energy Agency (dena)







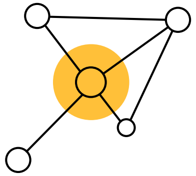


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Table of Contents

1. Overview of the scenario and study process

The CN100 scenario and the alternative pathways

Within this study, a so-called "Climate Neutrality 100 (CN100)" scenario is developed to examine how the goal of climate neutrality could be achieved in Germany by the year 2045.

The analysis presents a systematic transformation of the end-use sectors and the energy system within model boundaries.

The scenario is largely based on the Climate Protection Act 2021 (CPA, *Klimaschutzgesetz*) of the German government and, in addition to sector-specific climate targets for 2030, the scenario also considers the cross-sectoral emission reduction targets in subsequent years.

In addition to the main scenario CN100, four alterative pathways are analyzed. In these pathways, the level of electrification as well as developments in efficiencies are systematically varied from the transformation pathways of the end-use sectors assumed in the CN100 scenario.

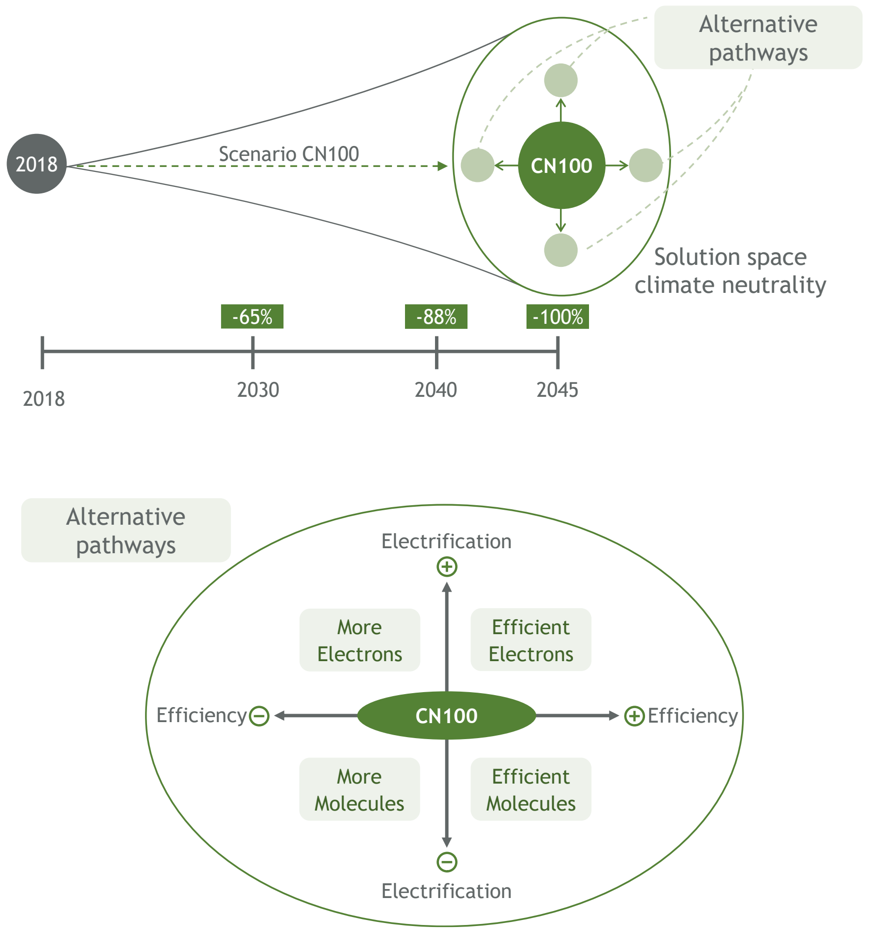


Figure 1: The scenario CN100 and alternative pathways

Study process and partner institutes

The dena pilot study is based on a multi-stakeholder approach.

Transformation pathways for sector-specific energy consumption are developed using bottom-up models for the end-use sectors industry and transport, completed by EWI, as well as buildings, completed by ITG/FIW Munich. The transformation pathway of the LULUCF sector is developed by the Öko-Institut.

The provision of the final energy use resulting from the exogenous transformation pathways is optimized using an energy system model developed at EWI.

Additional scientific, in-depth analyses are performed in order to ensure a well-founded definition of the transformation pathways, including a closer look at the

- development of the electricity grids (i.e., transmission and distribution grids), completed by ef.Ruhr,
- development of gas and hydrogen infrastructure as well as security of supply in extreme weather periods, completed by EWI.

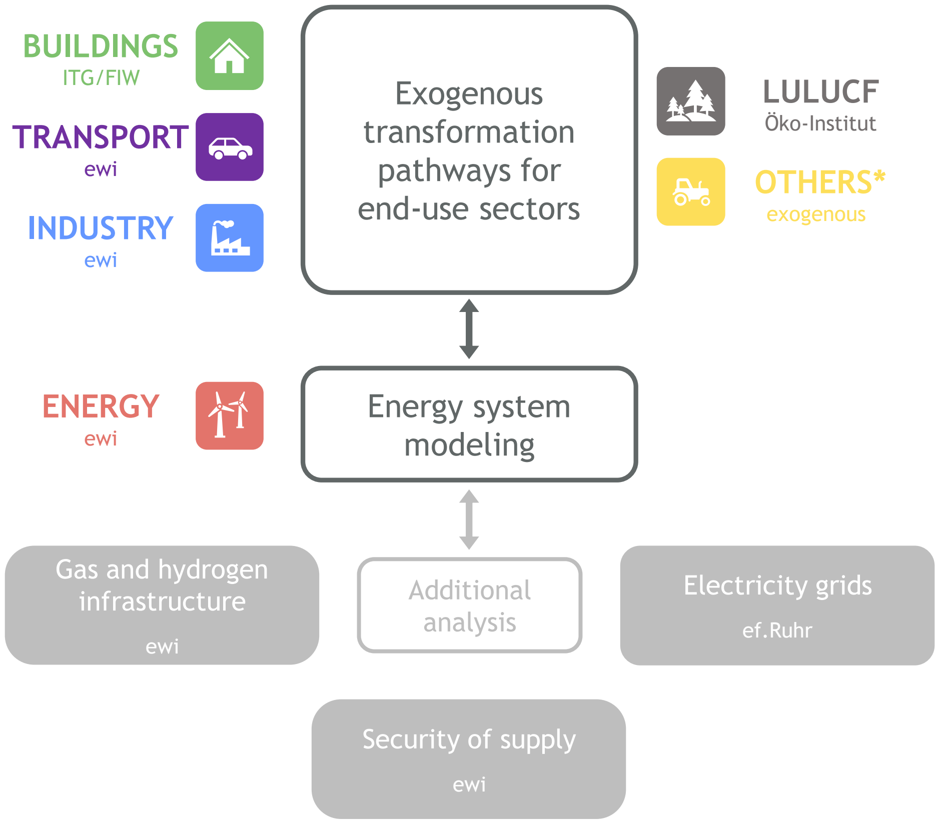


Figure 2: Overview of the methodical approach of the modeling
* Others include agriculture, waste and others

2. Final consumption in end-use sectors in the CN100 scenario

- Transport sector
- Industry sector
- Building sector

The transport sector

Figure 3: Technological and transformational approaches for decarbonizing the transport sector

E-Mobility

Higher technical efficiency of electric cars and a change in mobility behavior lead to a decrease in final energy consumption

Hydrogen

Higher market penetration of fuel cells (especially in heavy-duty transport)

Climate-neutral fuels

Use of synthetic and biogenic fuels where other decarbonization options are unsuitable

Gasoline and Diesel

Engine efficiency gains and a change in mobility behavior lead to a decrease in fuel consumption

Shift in the modes of transportation

Increased use of modes of transportation with lower emission intensity

Traffic volume

Decrease in traffic volume due to higher passenger use per vehicle

The transport sector

The Climate Protection Act 2021 aims to reduce emissions from the German transport sector to 85 Mt CO_2e by 2030 (for comparison: for the year 2021, the estimate is 148 Mt CO_2e). In the CN100 scenario, the transport sector is defined such that this sector-specific climate target is achieved.

In **passenger transport**, it is assumed that the annual demand increases only slightly up to 2050. However, the shares of the different modes of transportation in passenger mobility change significantly over time. A partial shift from national air and long-distance car travel to rail transport is assumed, as is an increasing shift from inner-city private vehicle use to public transport (e.g., buses and trams). Furthermore, a continuously growing share of micromobility, mainly in the form of bicycle use, is taken into account.

In **freight transport**, it is assumed that the annual demand increases by around 22 % by 2045 compared to 2018 values, primarily due to economic growth. In heavy-duty transport, hydrogen is used increasingly from 2030 onwards.

Final energy consumption in the transport sector decreases significantly over time. This results primarily from the shift to modes of transportation with lower emission intensity (e.g., public transport or rail) as well as the electrification of powertrains across the transport sector.

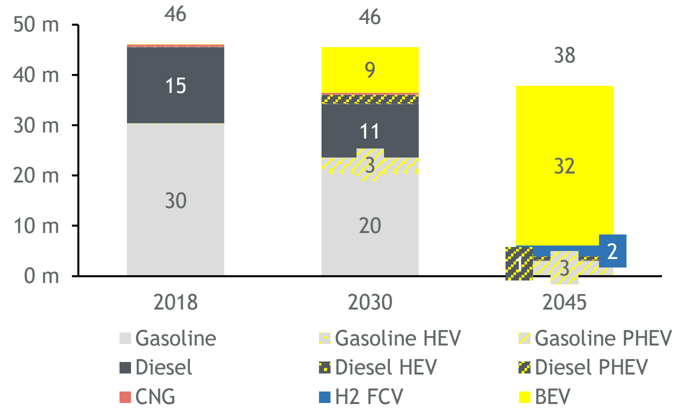


Figure 4: Development of the passenger car fleet

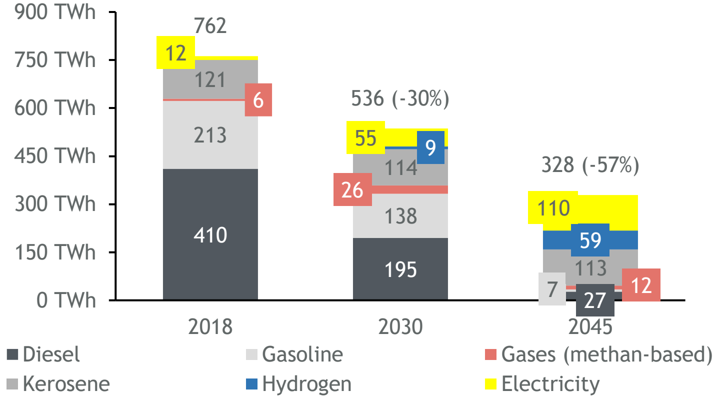


Figure 5: Final energy consumption in the transport sector

The industry sector

Figure 6: Overview of the technology transformation of selected industrial sectors

Products	Status quo: Technologies	Status quo: Main energy source	CN100: Technologies	CN100: Main energy source
Chemical				
Ammonia	▫ Haber-Bosch, Steam Methane Reforming (SMR)	▫ Electricity ▫ Natural gas (part. NE)	▫ Haber-Bosch, Electrolysis ▫ Haber-Bosch, H_2-Purchase	▫ Electricity ▫ Hydrogen (NE)
Aromatics & Olefins	▫ Steamcracking	▫ Naphtha (NE)	▫ Methanol-to-Olefins/-Aromatics ▫ Steamcracking	▫ Electricity ▫ Green Naphtha (NE)
Methanol	▫ Partial oxidation, heavy oil, Methanol synthesis ▫ SMR, Methanol synthesis	▫ Heavy oil (NE) ▫ Natural gas (NE) ▫ Electricity	▫ Electrolysis-hydrogen, Methanol synthesis ▫ Biomass gasification, Methanol synthesis	▫ Hydrogen (NE) ▫ Biomass (solid) (NE)
Iron & Steel				
Steel – Primary	▫ Blast furnace route	▫ Coking coal	▫ Direct reduction route with Electric arc furnace (DRI-EAF)	▫ Electricity ▫ Hydrogen (part. NE)
Steel – Secondary	▫ Electric arc furnace	▫ Electricity		▫ Electricity
Stones & Earths				
Lime	▫ Burnt lime	▫ Lignite ▫ Natural gas		▫ Electricity ▫ Hydrogen
Cement	▫ Semi-dry process ▫ Dry process	▫ Alternative fuels ▫ Hard coal	▫ Dry process	▫ Alternative fuels ▫ Hydrogen (10%) ▫ Biomass (solid) (5%)

NE = non-energetic

The industry sector

The Climate Protection Act 2021 aims to reduce emissions from the German industry sector to 118 Mt CO_2e by 2030 (for comparison: for the year 2021, the estimate is 181 Mt CO_2e). In the CN100 scenario, the industry sector is defined such that this sector-specific climate target is achieved.

The industry sector is characterized by a heterogeneous structure. In this study, the most energy- and emission-intensive industry types, i.e., chemicals, iron & steel and minerals, are examined in detail. Figure 6 (see previous slide) presents an overview of the current industry processes and the main energy sources as well as the technological developments assumed in the CN100 scenario.

In the industry sector, efficiency improvements make a significant contribution to reducing final energy consumption across all industry types. In addition, the adoption of innovative process technologies, changes in production volumes as well as higher recycling rates affect final energy consumption and greenhouse gas emission levels. For example, the introduction of innovative hydrogen-based direct reduction in steel production results in a fuel switch from coal to hydrogen, leading to significant savings in greenhouse gas emissions.

In addition, electricity consumption in the industry sector is assumed to increase due to, e.g., electricity use in low to medium temperature heat production as well as an increased adoption of electricity-intensive processes in the chemical industry (e.g., the methanol-to-olefins (MTO) or –to-aromatics (MTA) rotes) and the use of electrolyzers for ammonia production.

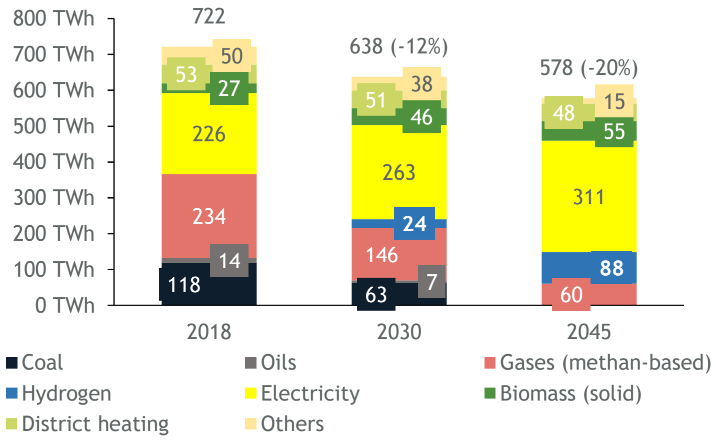


Figure 7: Final energy consumption in the industry sector

The building sector*

Figure 8: Transformation approaches for decarbonizing the building sector

Improvement of the building envelopes

Refurbishment of existing building envelopes to reduce energy demand

Energy efficiency standards for new buildings

Replacement of existing heating systems

Use of efficient and new heating technologies

E.g., expansion of district heating systems and adoption of heat pumps

Expanding the use of renewable energy resources

Use of synthetic and biogenic energy carriers

* The analysis and modeling of the building sector has been conducted by ITG Dresden/FIW Munich.

The building sector*

The Climate Protection Act 2021 aims to reduce emissions from the building sector to 167 Mt CO_2e by 2030 (for comparison: for the year 2021, the estimate is 115 Mt CO_2e). In the CN100 scenario, the building sector is defined such that this sector-specific climate target is achieved.

In the building sector, the energy refurbishment rate doubles from 0.85 % per year today to 1.9 % per year in 2045. The increased adoption of heat pumps as well as newer, more efficient heating technologies result in a reduction in the final energy demand as well as a decrease in the consumption of liquid (i.e., oil) and gaseous (i.e., methane-based gases and hydrogen) fuels.

The future of climate-neutral fuels and hydrogen in the building sector

In addition, the types of liquid and gaseous fuels (i.e., fossil, synthetic or biogenic) that are used change over time. By 2045, fossil oil is no longer consumed. The demand for liquid fuels is met using synthetic (80 %) and biogenically (20 %) produced oil. The demand for gaseous fuels in 2045 is covered by 30 TWh of biogenic gases and 11 TWh natural gas. The remaining 79 TWh are met using synthetic gas, namely hydrogen. The energy mix is a result of the energy system modeling performed by EWI.

Starting in 2030, hydrogen is consumed in the building sector (depicted as part of the gaseous fuel in Figure 10). Initially, hydrogen is blended into the gas distribution grids; however, by 2045, these pipelines are partially converted to hydrogen distribution networks. As a result, hydrogen consumption increases as a greater share of gas boilers become capable of using hydrogen (see section on gas and hydrogen infrastructure, p. 24).

* The analysis and modeling of the building sector has been conducted by ITG Dresden/FIW Munich.

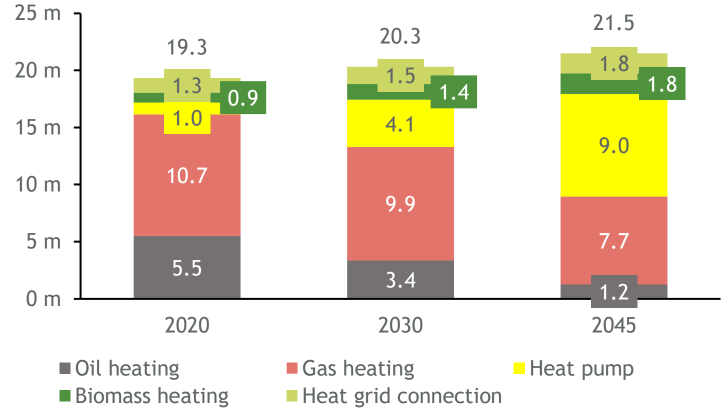


Figure 9: Heating structure in residential buildings

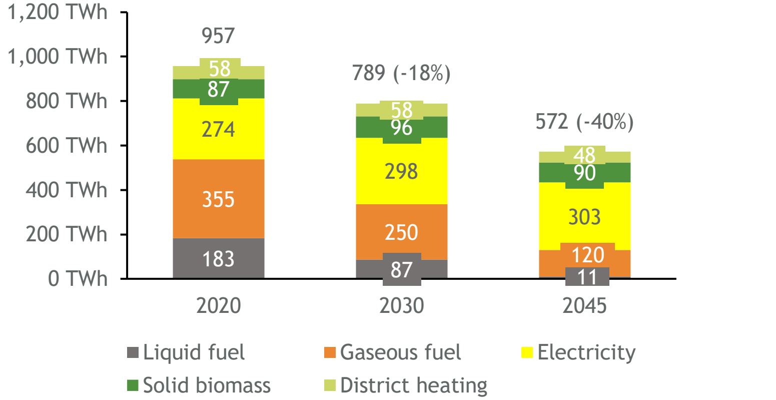


Figure 10: Final energy consumption in the building sector

Aggregated final energy demand

Electricity becomes the most important energy carrier in Germany, making up the largest share of final energy consumption in 2045.

Due to electrification of end-use applications and the need to substitute fossil oil and gas, a switch from fossil energy sources towards electricity and hydrogen takes place across all end-use sectors.

In addition to the growth in electricity consumption from electric vehicles, heat pumps and industrial processes, the expanding German hydrogen economy also drives electricity demand: Approximately 14 TWh of electricity is needed to produce 10 TWh of green hydrogen in 2030; and by 2045, electricity demand for electrolysis in Germany reaches 88 TWh.

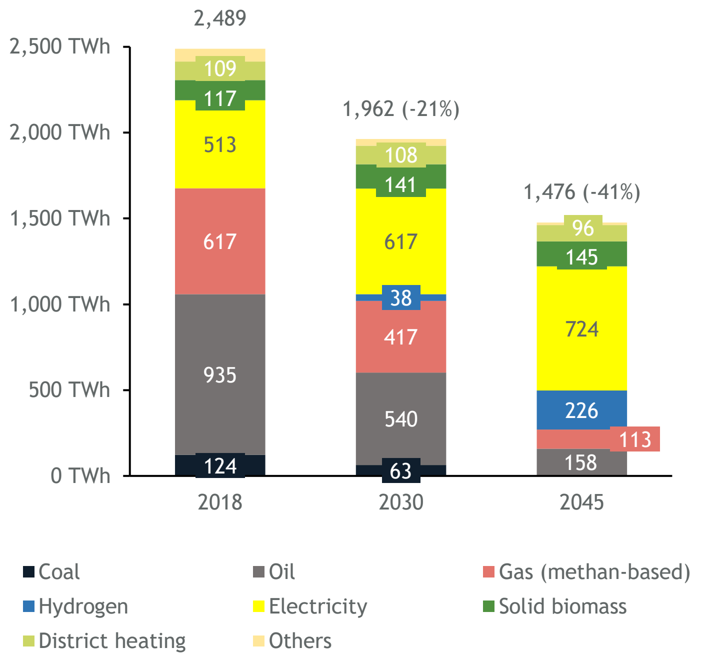


Figure 11: Final energy demand aggregated across all end-use sectors

3. Energy sector in the CN100 scenario

- Electricity generation
- Hydrogen demand
- Hydrogen supply
- Greenhouse gas emissions
- Security of supply
- Energy infrastructures

Electricity generation

The Climate Protection Act 2021 aims to reduce emissions from the energy sector to 108 Mt CO_2e by 2030. In the CN100 scenario, the energy sector is modeled such that this sector-specific climate target is achieved.

The CN100 scenario results show that electricity generation becomes virtually climate-neutral as early as 2040. In times of low electricity feed-in from renewables, hydrogen-capable gas-fired power plants are used as backup technologies.

Whereas the nuclear phase-out is completed by the end of 2022, the coal phase-out is determined by the market but at the latest in accordance with the legal requirements and the act on the phase-out of coal (Kohleausstiegsgesetz).

In 2030, the sharp decline in coal and nuclear power generation is partially offset by an increase in gas-fired power generation. From 2040 onwards, these power plants run predominantly on hydrogen.

Germany changes from a net electricity exporter to a net importer from 2030 onwards due to, e.g., the phase-out of nuclear power as well as the pressure to reduce emissions in the energy sector and the corresponding decline in conventional power generation.

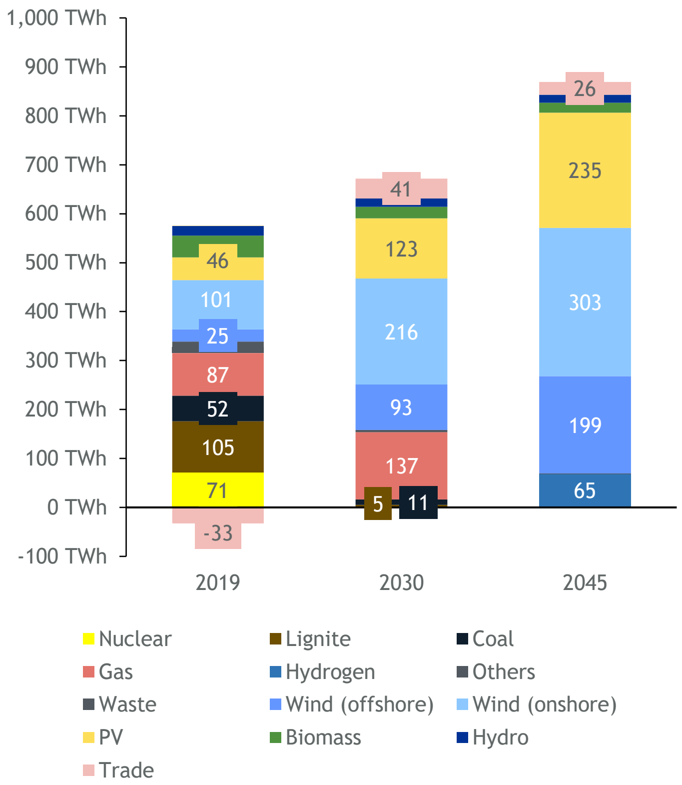


Figure 12: Net electricity generation by energy source

Hydrogen demand

In the CN100 scenario results, a rapidly growing hydrogen economy already begins to develop before 2030 in Germany. Green and blue hydrogen as well as synthetic power-to-liquid reduce overall CO_2 emissions, especially in applications where electrification is either not possible or comes with high costs.

This holds true, for example, in the case of high-temperature heat in industrial processes, heavy-duty transport or aviation. Furthermore, hydrogen is blended into the gas grid on a small scale.

The steel and chemical industries, in particular, use large quantities of hydrogen early on especially for high-temperature heat .

In addition, in 2030, PtL is used mainly in aviation. By 2045, the major consumers of PtL include road (e.g., heavy-duty transport), rail, inland waterway transport and the chemical industry.

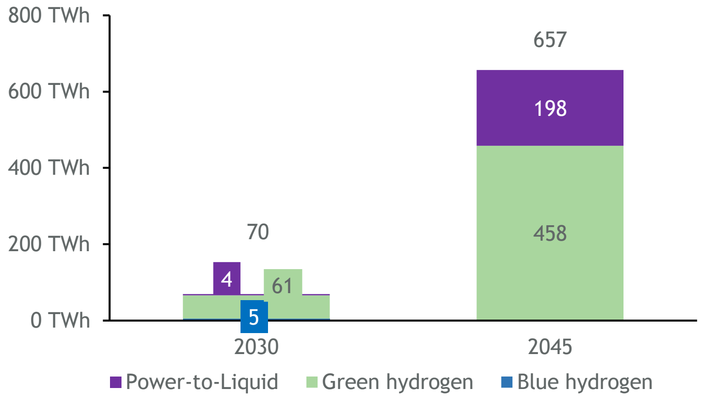


Figure 13: Demand for hydrogen and downstream products

Hydrogen supply

In the CN100 scenario results, global efforts to reduce greenhouse gases lead to a ramp-up of hydrogen production, processing and trade on the European as well as global level. As a result, hydrogen and other synthetic energy carriers are able to be imported from regions with more favorable conditions for electricity generation from renewable energy sources.

Domestic hydrogen production also experiences a ramp-up. Consistent with the goals of the German National Hydrogen Strategy, a total electrical capacity of 5 GW of electrolyzers is installed in Germany by 2030. In 2040, the capacity of electrolyzers exceeds the 10 GW defined in the hydrogen strategy, reaching 13 GW. However, imports from other European countries account for the largest share of the hydrogen supply.

In addition, large quantities of hydrogen are imported by pipeline from North Africa, Eastern Europe (Russia and Ukraine) and Turkey.

The production of other synthetic energy carriers requires large amounts of renewable electricity. Limitations in renewable resources (i.e., restricted availability of areas for renewable energy generators as well as relatively lower quality of production sites) cause PtL production in Germany to be comparatively expensive. However, high energy density and stable liquid phase of PtL energy carriers allow them be transported at low cost, resulting in Germany importing PtL from more distant regions of the world. In the CN100 scenario results, all PtL imports in 2045 come from the Middle East, Australia and South America, particularly Chile and Colombia.

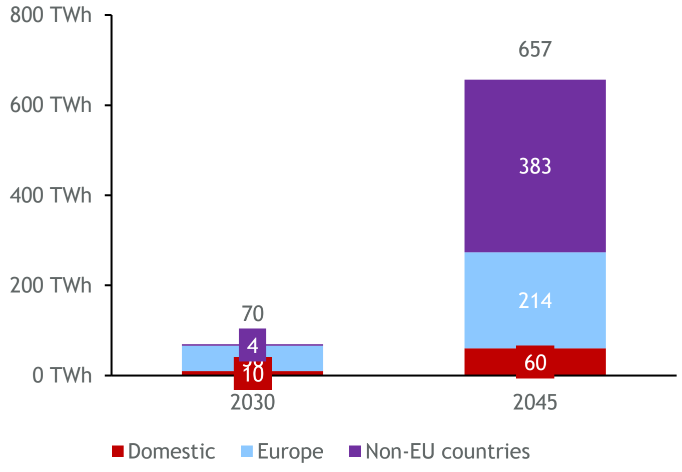


Figure 14: Origin of hydrogen and downstream products

Greenhouse gas emissions

The end-use sectors buildings, transport and industry achieve their emission reduction targets in accordance with the requirements of the Climate Protection Act 2021. The energy sector, on the other hand, is able to overachieve its target mainly due to the accelerated coal phase-out.

Climate neutrality in Germany is achieved in 2045. The transport sector becomes completely climate neutral; however, in the building and industry sectors, small net residual emissions remain. In the industry sector, remaining process emissions and energy emissions are not fully offset by technical sinks and CO_2 abatement options. In the building sector, natural gas is still used to a small extent. To counteract the residual emissions from these two sectors, the energy sector achieves a net negative emissions balance through the use of carbon capture and storage (CCS) at biomass cogeneration and waste incineration plants.

The residual emissions in the agriculture sector are offset by forests and other natural sinks in the LULUCF-sector.

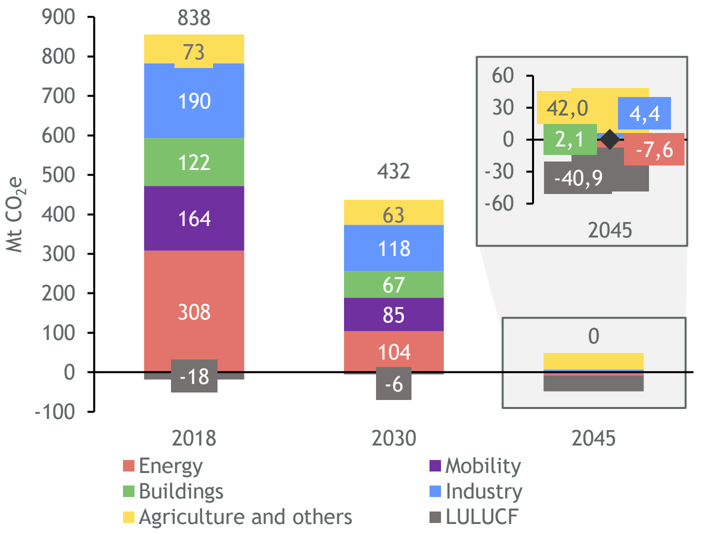


Figure 15: Development of net greenhouse gas emissions

Security of supply

The simultaneous peak demand of the end-use sectors is considered to be the maximum inflexible load that must be met by the power plant fleet, even in times of low electricity production by renewables.

Simultaneous peak demand increases in the medium term mainly due to the emergence of new temperature-dependent loads (e.g., heat pumps and other electrical heating) and greater electrification in the industry sector. Per assumption, the simultaneous peak demand can be reduced by about 4 GW through demand flexibility in the industrial sector (i.e., via DSM and interruptible loads). All other loads are assumed to be inflexible during the peak hour.

Imports from other countries are assumed to contribute only 10 GW to the secured capacity. This corresponds to an estimate of the reliable contribution even in situations with low availability and simultaneously high load in neighboring European countries.

In the medium term, the maximum inflexible load (i.e., the high residual loads assumed) is mainly covered by gas-fired power plants, which compensate for the reduced dispatchable power plant capacity resulting from the coal and nuclear phase-outs. Batteries and pumped storage also play a role in the provision of firm power. The power plants used to supply firm capacity do not necessarily refinance themselves on the market as these are rarely used.

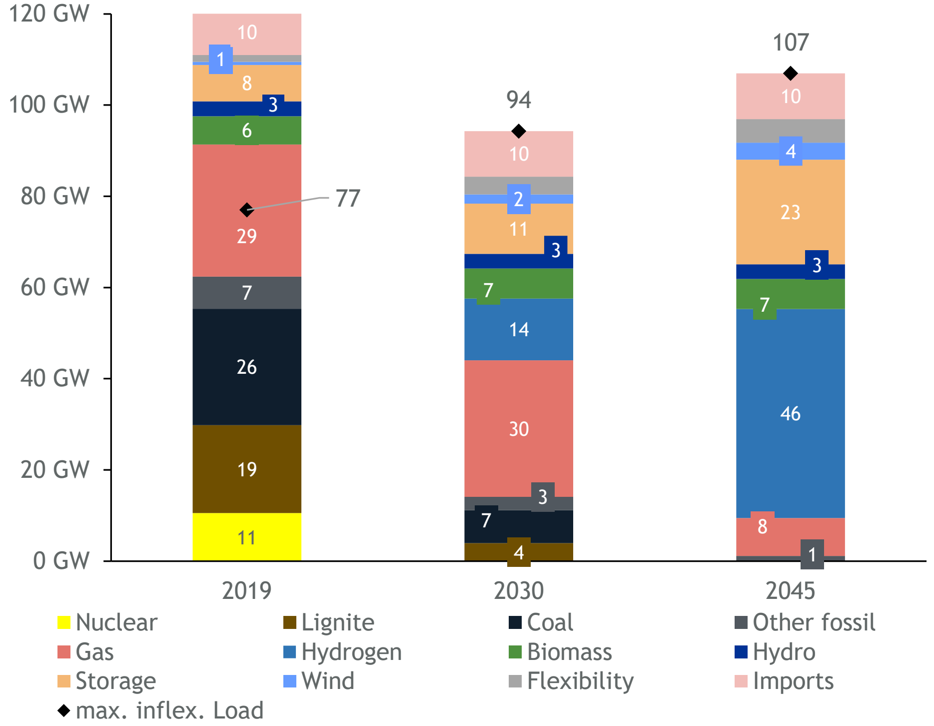


Figure 16: Development of inflexible peak demand and provision of firm power plant capacity by energy carrier

Taking a closer look: Security of supply in extreme weather situations*

DIMENSION uses weather data based on the year 2015 as well as synthetic high residual demands when optimizing the power plant fleet. However, in order to test the security of supply, residual load time series for 35 weather years (1982-2016) were generated to identify critical situations beyond the meteorological scope of the model. Two extreme weather periods with residual loads higher than those already considered by the model were identified: 7 days in January 1997 and 14 days in December 2007.

A meteorological analysis of the periods confirms that the 1997 period was unusually cold. However, even though western Europe experienced persistent doldrums, wind production from northern Europe and hydro production in France and Switzerland remained available.

Hourly dispatch calculations confirm that despite the extreme nature of the two weather periods, supply is reliable for the 2007 period and only minor supply gaps occur for the 1997 period, namely an interruption of 1,4 GW for one hour in the year 2030 of the CN100 scenario. A sensitivity analysis considering household flexibility shows that load curtailment can be avoided if heat pumps and electric vehicles are able to shift their load by 2 and 4 hours, respectively, using thermal and/or battery storage.

As such, additional interconnectors between Germany and France as well as between Germany and Switzerland assumed for 2045 in the CN100 scenario prevent supply disruptions.

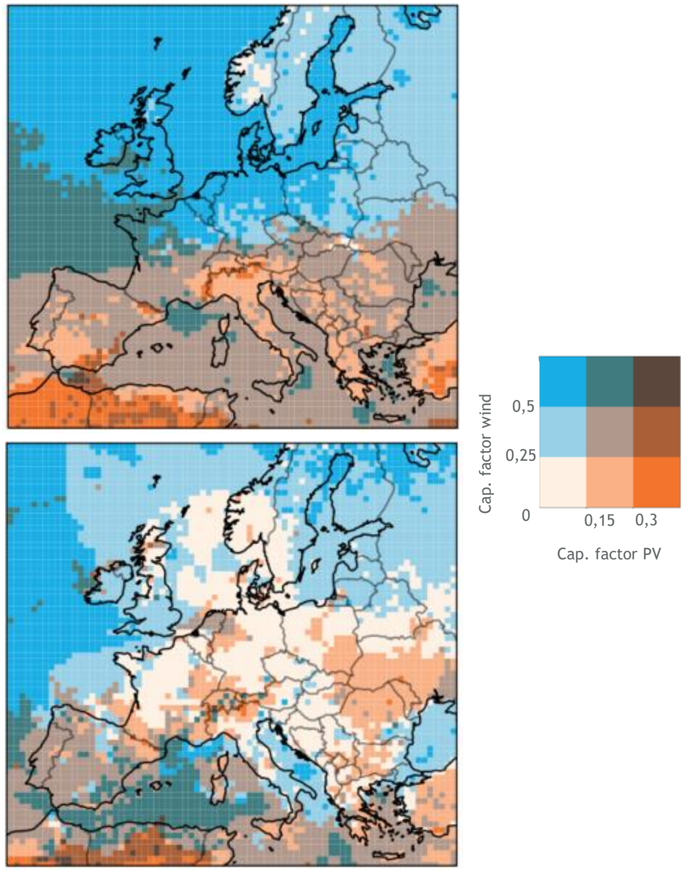


Figure 17: Capacity factors for wind and PV generation - 1995-2014 long term mean of winter (DJF) (top) and January 1997 (bottom)

* The analysis on extreme weather situation has been conducted by Prof. Stephanie Fiedler and Linh Ho.

Energy infrastructure - Electricity*

Based on the CN100 scenario results, a grid model was used to estimate capacity expansion requirements for transmission and distribution systems for the target years 2030 and 2045. Load flow calculations show that required transmission system expansion in the CN100 scenario exceed the capacity of projects currently approved in the German Grid Development Plan (GDP). Specifically, transmission system capacity from the B2035 Scenario of the 2020 GDP planned for 2035 needs to be available already by 2030. This results in an additional need of around 2.700 line-kilometres in the transmission network compared to the GDP scenario. By 2045, an 8,200 additional line kilometres are required compared to the GDP. This corresponds to additional investments of about 6.7 billion EUR up to 2030 or 19.3 billion EUR up to 2045. To reach these capacities, a significant acceleration of grid expansion in Germany is necessary.

The modeling of network expansion requirements at medium-voltage (MV) and low-voltage (LV) levels is based on grid expansion calculations for representative grids, which are then extrapolated to examine Germany as a whole. The analyses show a grid expansion requirement of 26 billion EUR for the LV level and 17 billion EUR for the MV level by 2030. By 2045, the analyses show an expansion requirement of EUR 75 billion for the LV level and EUR 40 billion for the MV level. On the LV level, metropolitan areas are particularly affected. The annual expansion of the lines on both grid levels found in the results is of the same order of magnitude as historical values and is thus considered to be feasible. It should be noted that the availability of residual load-smoothing, grid-serving control of electric vehicle charging at private charging points was assumed for planning purposes. Uncontrolled charging, as considered in the grid planning today, would lead to a considerably higher need for grid expansion.

The need for grid expansion at the high-voltage level (HV level) is estimated using extrapolation based on the results of the dena-distribution grid study (dena, 2012) and the assumed expansion of renewable energy generators in the CN100 scenario. This leads to an assumed investment requirement in the mid (2030) and high (2045) double-digit billion EUR range.

* The analysis and modeling of the electricity grid has been conducted by ef.Ruhr.

Energy infrastructure - Gas and hydrogen

Based on the CN100 scenario results, the study takes a detailed look at the necessary gas and hydrogen infrastructure. Changes in consumption behavior have a major influence on infrastructure use. Total gas consumption initially decreases slightly between 2018 and 2030, followed by a significant decrease up to 2045 (see Figure 18).

In the short term, a domestic transport grid for hydrogen could initially be developed in northwestern Germany to connect large industrial clusters in the border triangle between Germany, Belgium and the Netherlands (Fernleitungsnetzbetreiber, 2021; Agora Energiewende & AFRY Management Consulting, 2021; Jens et al., 2021). This domestic transport grid could expand over time towards the southwest region and, by 2040, could connect southern Germany to the rest of the hydrogen transport grid. Furthermore, the historical development of gas transport infrastructure has led to the existence of parallel gas pipelines across Germany. As such, relative to the regional demand, certain pipelines could be converted for the transport of hydrogen.

In the distribution and local gas grids, parallel pipelines rarely exist. Therefore, the coexistence of two gas families within a distribution grid network is not considered within this study. The switch from gas family methane to hydrogen means that, in the long run, a large share of the gas distribution grid is converted to transport hydrogen.

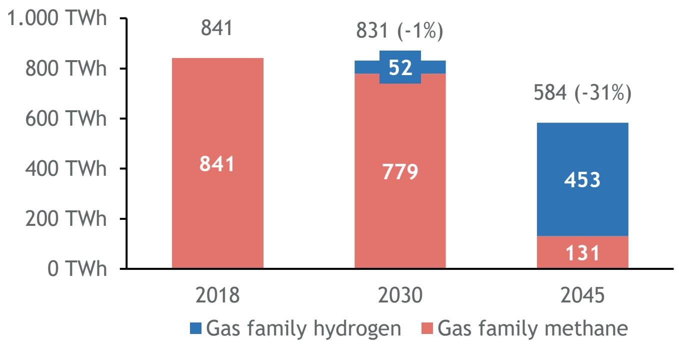


Figure 18: Energy consumption by gas family

4. Alternative pathways

- Design of the alternative pathways
- Transport sector
- Industry sector
- Building sector
- Energy sector

Design of the alternative pathways

In addition to the CN100 scenario, four alternative pathways are analyzed.

In the alternative pathways, the transformation pathways of the end-use sectors considered in the CN100 scenario are systematically varied with respect to the electrification level as well as efficiency developments.

These variations to the transformation pathways affect the composition of final energy demand in terms of electricity and molecule-based energy carriers such as hydrogen, methane-based gases and liquid mineral oil-based fuels.

Alternative pathways are examined for the following end-use sectors: (see Figure 20, next slide):

- Industry sector: “Other Industries”
- Building sector: Residential and non-residential buildings and trade, commerce and services (TCS) processes
- Transport sector: Passenger cars

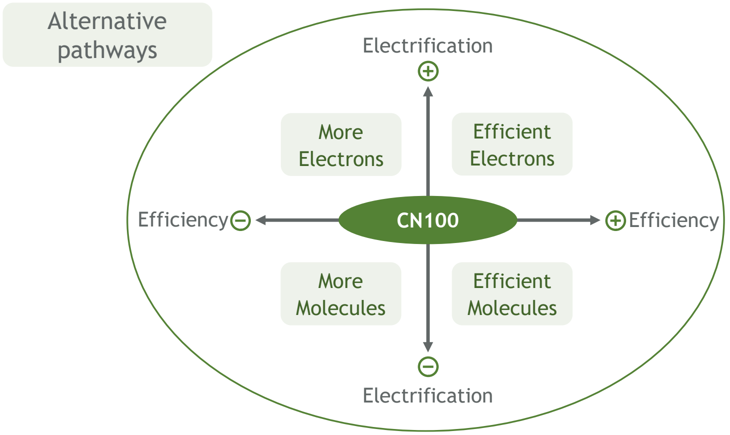
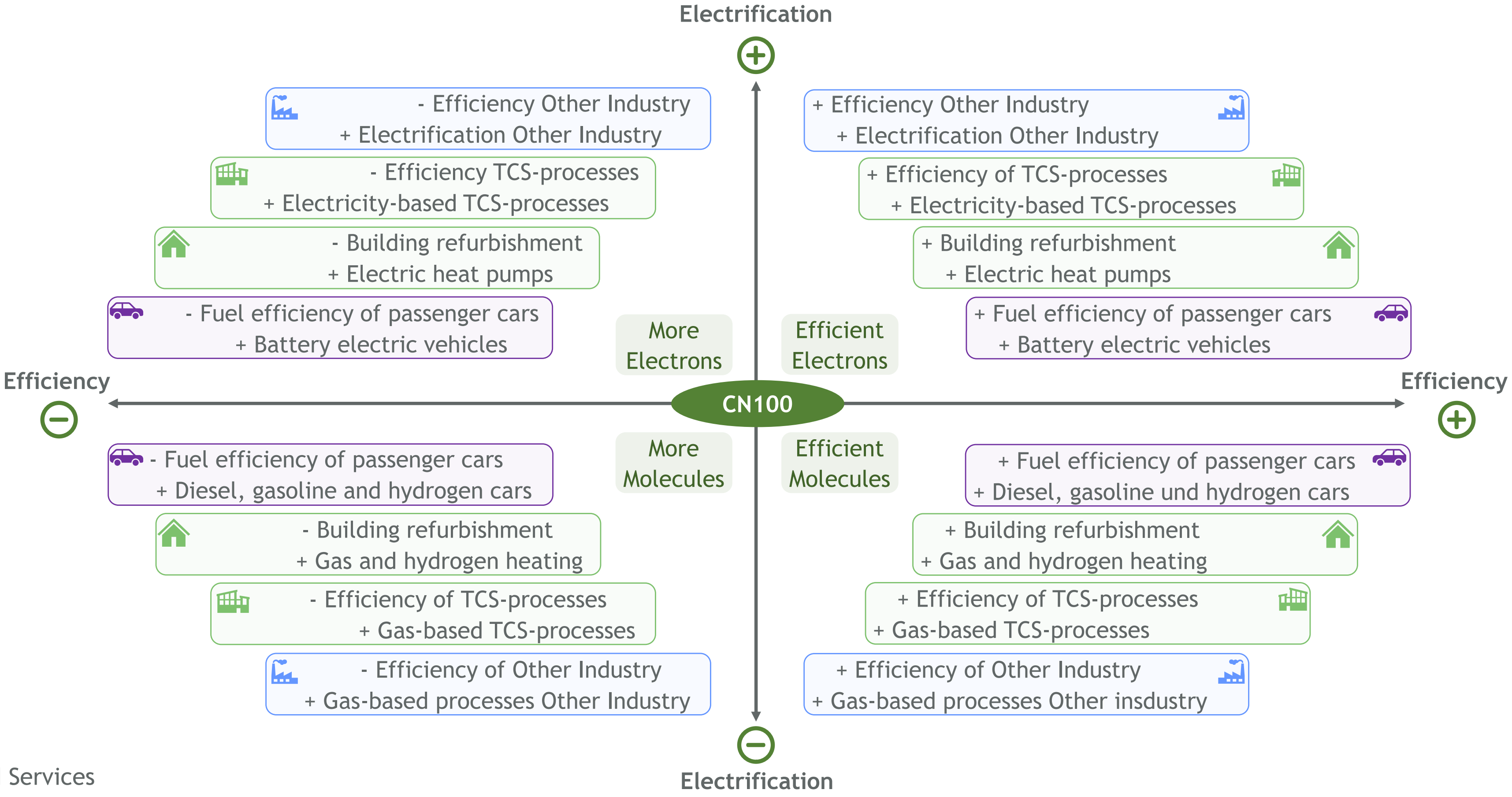


Figure 19: The alternative pathways considered

Design of the alternative pathways

Figure 20: : Overview of the design of the alternative pathways



TCS = Trade, Commerce and Services

Transport sector

In the case of passenger cars, the market penetration and fuel efficiency of electric vehicles as well as conventional drivetrains (e.g., diesel or gasoline) considered in the CN100 are varied.

In the "Molecules“ pathways, the vehicle mix in the passenger segment is assumed to have a greater share of conventional drivetrains than in the CN100 scenario. This pathway represents a world in which electromobility can only slowly increase its market share.

In the "Electrons" pathways, on the other hand, a higher number of electric vehicles is assumed as in the CN100 scenario.

In the “Efficient” pathways, specific fuel consumption of passenger cars is decreased compared to the values in the CN100 scenario. This is based on the underlying assumptions that technological improvements develop faster than those assumed in the CN100 scenario and that end consumers increasingly switch to smaller, lighter vehicles.

In contrast, specific fuel consumption is higher in the “More” pathways than in the CN100 scenario, which assume that technical progress takes place more slowly and passenger cars become bigger and heavier.

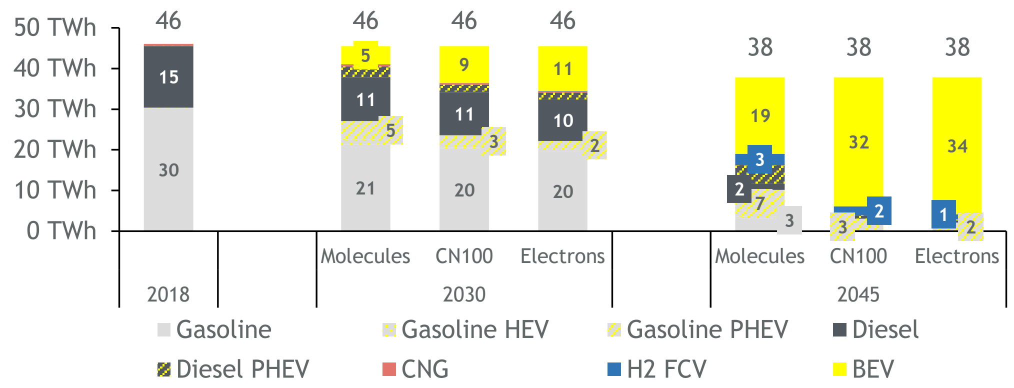


Figure 21: Vehicle mix in the alternative pathways compared to the scenario CN100

Industry sector

In the alternative pathways, variations in the sector “Other Industries” are considered.

In “Other Industries”, a large share of cross-sectional technologies allows for high potential for efficiency improvements. These technologies are not limited to one industry type but rather used throughout the industry sector and include pumps, compressors, electric motors as well as heat-generating technologies such as gas condensing boilers and heat pumps. In the CN100 scenario, cumulative efficiency gains of approximately 34 % are realized by 2045. The alternative pathways seek to examine the effects of lower (“More”) or higher (“Efficient”) efficiency developments.

In the CN100 scenario, a switch to electricity-based technologies is assumed due to the efficiency advantages of certain electric systems relative to gas-based options (e.g., heat pumps). The effects of a lower (“Molecules”) or higher (“Electrons”) degree of electrification are reflected in the definition of the alternative pathways.

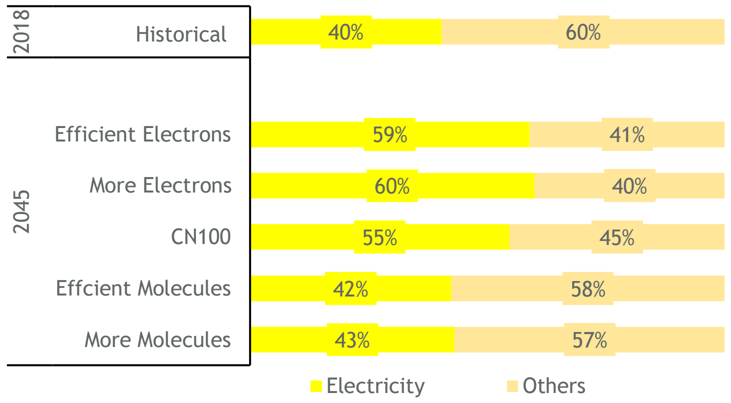


Figure 22: Share of electricity in final energy consumption by “Other Industries“ in the alternative pathways compared to the scenario CN100

Building sector*

With regards to the buildings sector, the alternative pathways consider variations in the market penetration of heat pumps as well as in building renovation rates.

In the "Electrons" pathways, a higher market penetration of electric heat pumps is assumed and, at the same time, a sharper decrease in the share of buildings heated with liquid and gaseous energy sources compared to the CN100 scenario results.

The "Molecules" pathways, on the other hand, assumes a lower expansion of electric heat pumps.

In the “Efficient” pathways, the building renovation rates are higher than in the CN100 scenario, whereas the “More” pathways assume lower building renovation rates.

Additionally, alternative pathways for the sector "Trade, Commerce and Services" are also examined, which are similar to the pathways defined for “Other Industries” (see previous slide).

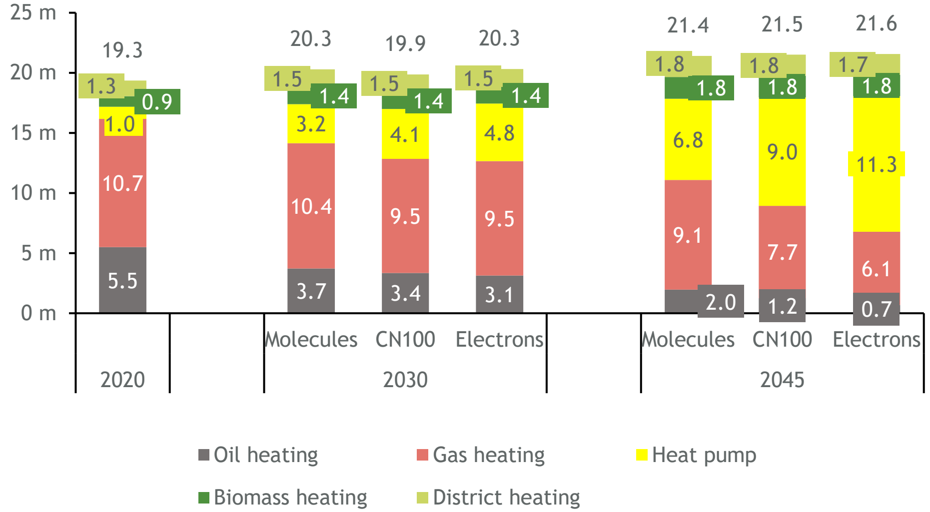


Figure 23: Heating structure in residential buildings in the alternative pathways compared to the scenario CN100

* The analysis and modeling of the building sector has been conducted by ITG Dresden/FIW Munich.

Energy sector

The final energy consumption of the end-use sectors in the alternative pathways deviate in the level and structure from those found in the scenario CN100.

Due to the variations in final energy consumption, the (climate-neutral) energy supply is also affected, especially with regards to electricity generation and the use of climate-friendly hydrogen and synthetic energy sources.

The following slides present the results of the alternative pathways. As a reference, the key results of the scenario CN100 are shown in Figure 24.

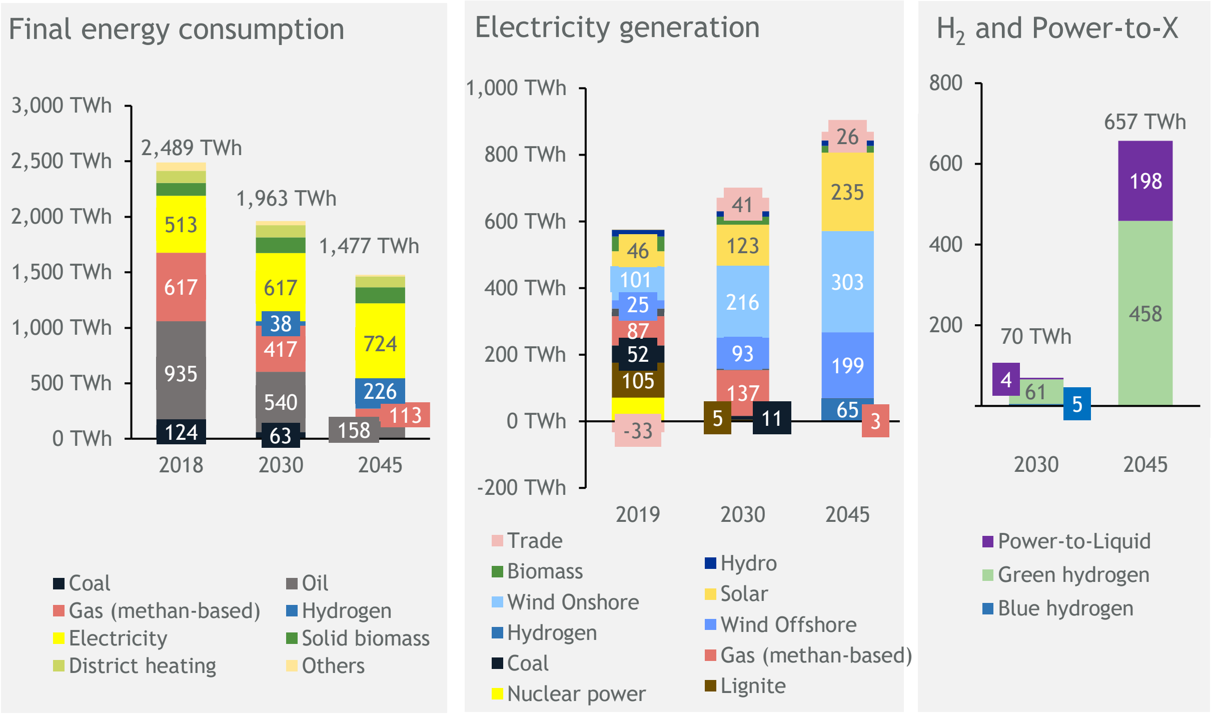


Figure 24: Overview of the key results of the scenario CN100

Energy sector - Efficient Electrons

In the alternative pathway "Efficient Electrons", electricity demand increases due to the higher number of heat pumps, electric cars and electrified industrial processes.

In 2030, the increase in electricity demand causes an increase in electricity generation from methane-based gases and biomethane. In addition, higher emission reductions in the building sector due to, e.g., ambitious building renovation rates result in less pressure to reduce emissions in the energy sector, allowing for lignite to remain in the power generation mix.

The demand for hydrogen and PtL decreases in the alternative pathway "Efficient Electrons" because of changes in the consumption behavior in the end-use sectors.

In addition, the use of hydrogen in the energy sector decreases compared to the CN100 scenario results as lower gas demand in the end-use sectors allows for biomethane to be available for use in the energy sector.

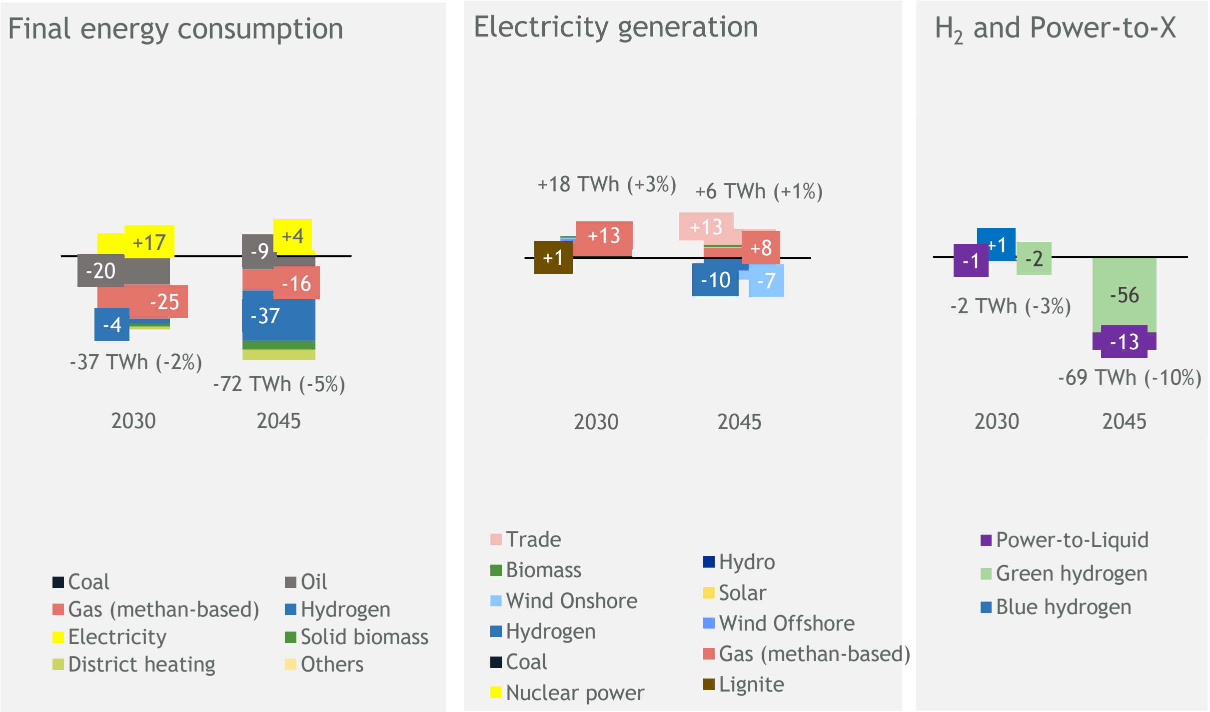


Figure 25: Overview of the key results of the „Efficient Electrons" pathway

Energy sector - More Electrons

In the alternative pathway “More Electrons”, electricity demand increases due to the higher number of heat pumps, electric cars and electrified industrial processes. This demand is significantly higher than in "Efficient Electrons" scenario, which is due to lower efficiencies in the industrial and transport sectors as well as lower building renovation rates.

Additional electricity demand is largely met by low-emission generation (primarily wind energy) and imports. Because the simultaneous peak load increases with the electricity demand, more dispatchable power plants must be added.

Less hydrogen and hydrogen derivatives are demanded in the “More Electrons” pathway compared to the CN100 scenario results as fewer gas- and oil-based technologies are used.

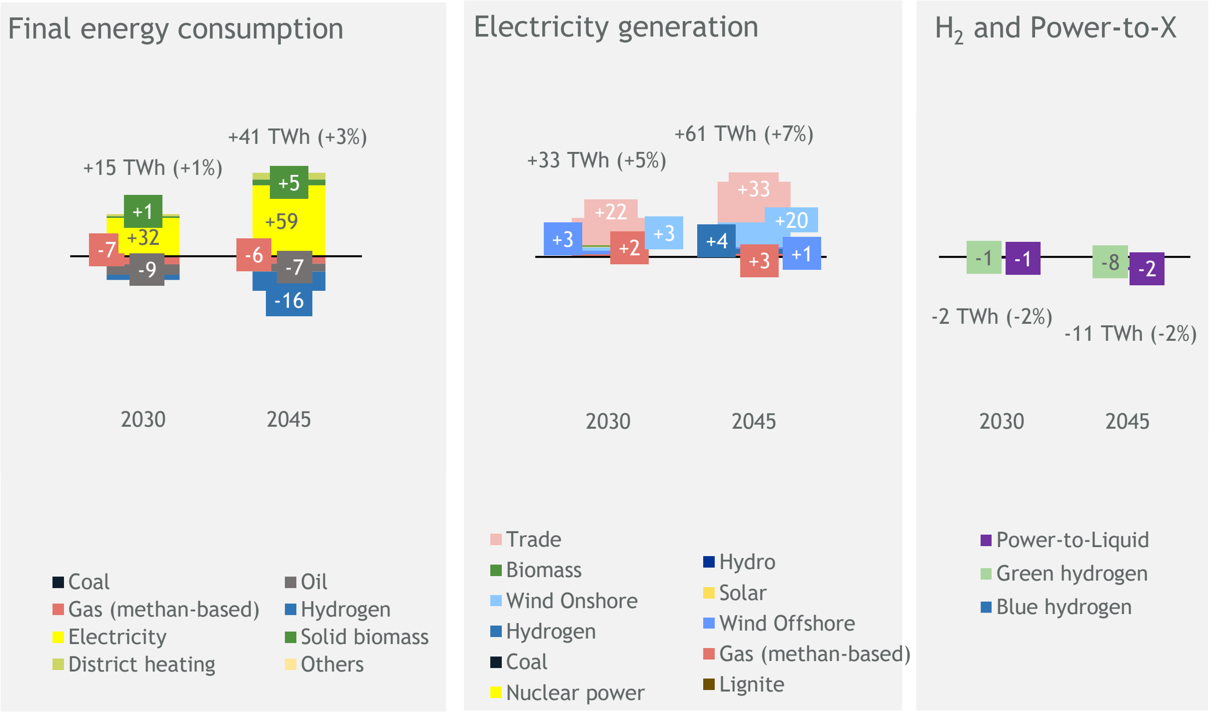


Figure 26: Overview of the key results of the „More Electrons“ pathway

Energy sector - Efficient Molecules

In the alternative pathway "Efficient Molecules", the electricity demand is lower compared to the CN100 scenario results. This is due to the combined effect of higher efficiency gains and lower electrification. Due to the lower electricity demand, renewable energy generation, gas/hydrogen generation and imports decrease compared to the CN100 scenario results.

In the "Efficient Molecules" pathway, more PtL is needed to meet the sector targets - in particular, in the transport and buildings sectors. On the other hand, the demand for green hydrogen decreases slightly compared to the CN100 scenario results as the lower electricity demand requires less hydrogen consumption in the power sector.

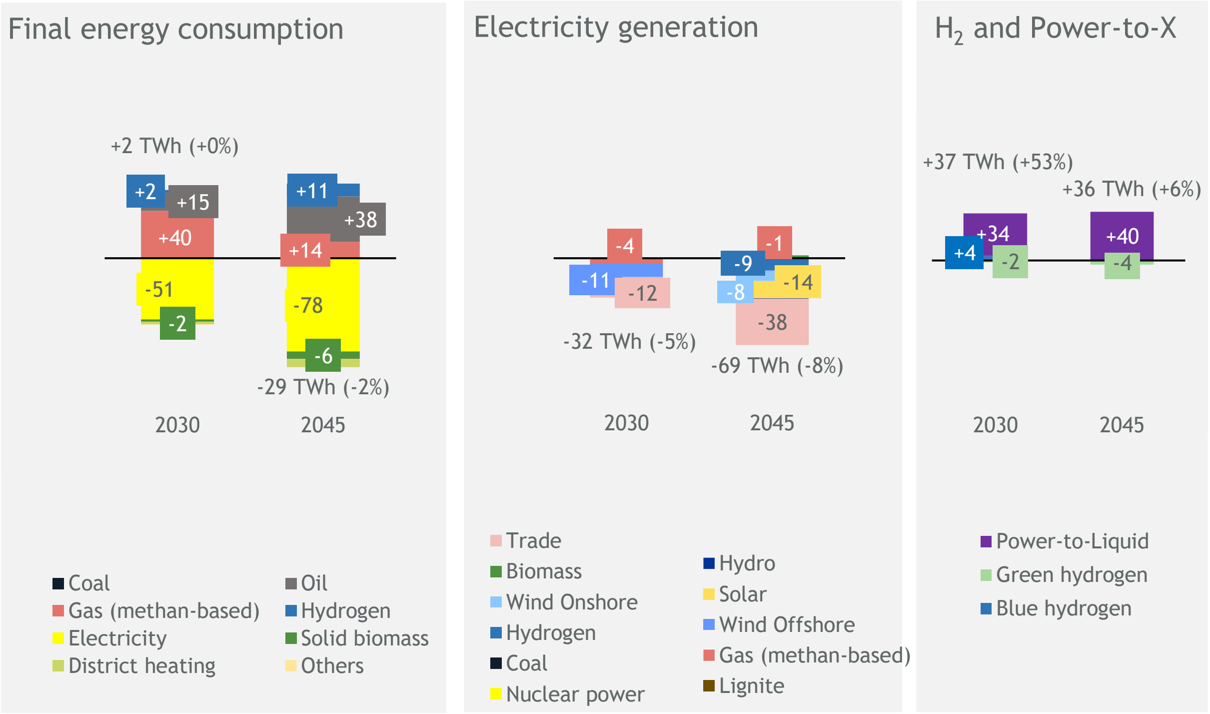


Figure 27: Overview of the key results of the „Efficient Molecules“ pathway

Energy sector - More Molecules

The largest differences in final energy demand compared to the scenario CN100 are seen in the results of the "More Molecules" pathway.

The demand for electricity is below the CN100 scenario, whereas the demand for gaseous and liquid energy sources is significantly higher.

With regard to electricity generation, the results of the "More Molecules" pathway are similar to those seen in the "Efficient Molecules" pathway. However, there is a more moderate decline in electricity demand from the end-use sectors as efficiency gains are assumed to be lower than in the scenario CN100 or the "Efficient Molecules" pathway.

In the "More Molecules" pathway, there is significantly more demand for gaseous and liquid energy carriers than in the scenario CN100. The industrial sector also uses more hydrogen. The realization of these results would require a rapid ramp-up of PtL production by 2030, which makes the feasibility of this pathway rather questionable.

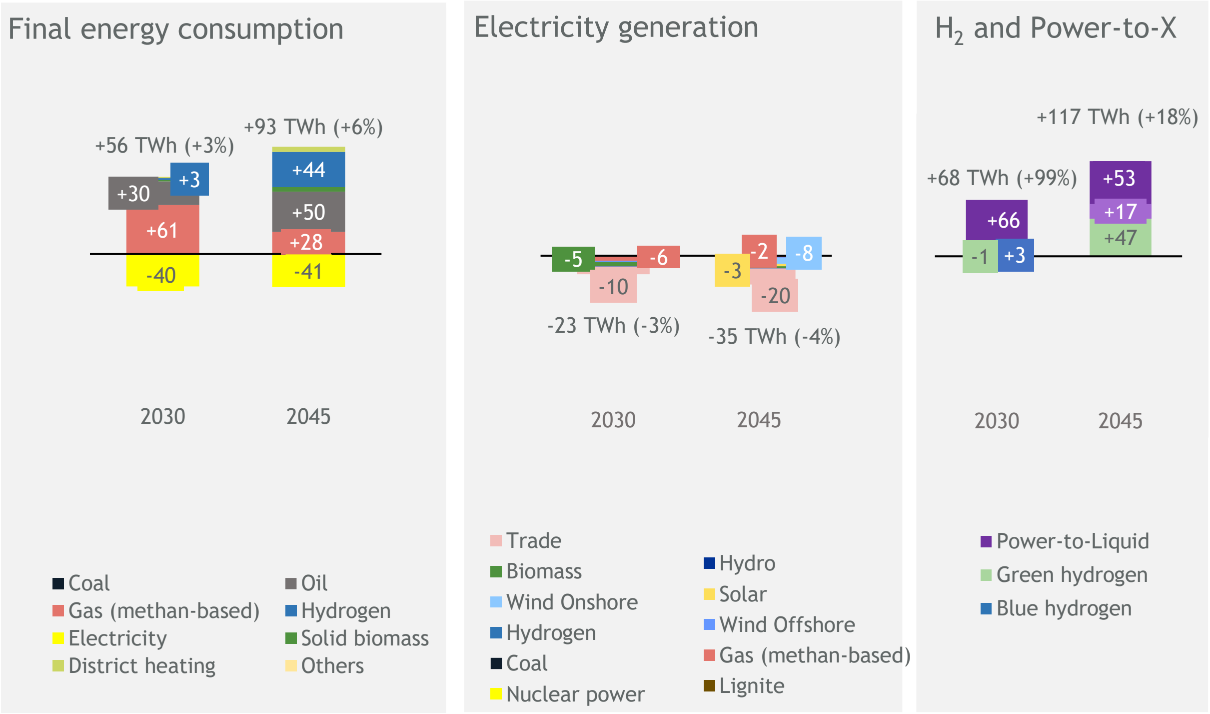


Figure 28: Overview of the key results of the „More Molecules“ pathway

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BEV	Battery electric vehicles
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CO_2e	CO_2-equivalents
CNG	Compressed natural gas
dena	German energy agency (Deutsche Energie-Agentur GmbH)
DRI-EAF Route	Hydrogen-based direct reduction and subsequent melting in electric arc furnaces
EWI	Institute of Energy Economics at the University of Cologne
FCEV	Fuel cell electric vehicles
MV	Medium-Voltage
FIW	Forschungsinstitut für Wärmeschutz e. V. Munich
GW	Gigawatt
ITG	Institute for Building Systems Engineering Dresden Research and Application GmbH
CN100	Climate neutrality 100 (Scenario)
CPA	Climate protection act (Klimaschutzgesetz)
LNG	Liquified natural gas
LULUCF	Land Use, Land Use Change and Forestry
m	Million
Mt	Megatons
LV	Low-Voltage
MTO/MTA	Methanol-to-Olefins/-Aromatics-Route
NE	Non-energetic
PHEV	Plug-in hybride vehicles
PtL	Power-to-Liquid
PV	Photovoltaic
SMR	Steam Methane Reforming
TWh	Terawatt hours
GDP	Grid Development Plan
TCS	Trade, Commerce and Services

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