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Long-term Scenarios for the Transformation of the Energy System in Germany III

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Long-term Scenarios III – Summary Report

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Table of contents

1 Executive Summary

The research project "Long-term Scenarios for the Transformation of the Energy System in Germany III" examines the techno-economic impacts of certain pathways that lead to the decarbonisation of the energy system and thus contribute to Germany's greenhouse gas neutrality before 2050. Specifically, three scenarios are examined and modelled in this report. Decarbonisation requires climate-neutral energy sources. These can be either electricity, hydrogen or synthetic hydrocarbons. For this first report, we model one scenario for each energy carrier that is characterized by a heavy use of the respective energy carrier throughout the energy system (GN-Electricity, GN-H2-G, GN-PtG/PtL). Further scenarios will follow. The following insights can be derived from the comparison of the three scenarios.

The industrial sector is facing a profound transformation in many industries and value chains. Without large quantities of CO_2-neutral secondary energy sources (electricity, H2, PtG), a transformation is not possible. Energy-intensive primary industries in particular are facing a comprehensive conversion of their plant stock. In addition, the capture and possibly the use of CO_2 from process emissions, e.g. in the cement industry with the corresponding transport infrastructures, is an issue that becomes relevant in all scenarios.

According to current knowledge, an increase in the direct use of electricity for heat supply through heat grids in areas where this is possible, a significant increase in heat pumps in buildings and an electrification of large parts of car and commercial transport is a robust strategy.

Air and maritime transport will still dependent on hydrocarbons in the long term, which can be provided from biogenic sources or possibly from synthetic hydrocarbons.

For long-distance transport, process heat, poorly insulated buildings and many industrial processes, various technical solutions are conceivable, but with different consequences. In the case of poorly insulated buildings, the options are: the use of expensive synthetic hydrocarbons or, to a very limited extent, biomass; the use of hydrogen with the corresponding effort in converting appliances and the supply infrastructure; and the direct use of electricity with re-insulation, if possible.

In all scenarios, a high expansion of renewable energies in Germany and Europe is a central finding and key to any future energy system. The main challenge lies in the availability of land and the necessary social acceptance for such a high renewables expansion. Furthermore, the electricity grid must be expanded significantly in all scenarios. Efficient sector coupling (i.e. including flexibility of demand) and a transformation of the heat grids are also central elements for the integration of renewable energies.

Germany will continue to import energy in 2050. However, the imported energy sources will change. There is a considerable amount of land use outside of Germany, especially for PtG imports. Energy efficiency is an important building block of the energy transition in order to reduce the land pressure from electricity generation from renewable energies both at home and abroad. The development of a European hydrogen network is part of a robust strategy for many possible scenarios. In this context, adapting the gas grid to declining methane demand and the transport of hydrogen is an important task.

Speculating on the large-scale use of synthetic hydrocarbons is a risky strategy, as the economic impact of this scenario is only conceivable under very specific conditions.

Furthermore, our analyses show that, according to current knowledge, greenhouse gas emissions in Germany cannot be completely reduced to zero. For this reason, the research and development of technologies for negative emissions should also be advanced.

2 Introduction

2.1 Objective

Germany's energy and climate policy goals require a fundamental restructuring of the energy system that affects almost all sectors of the economy. On behalf of the Federal Ministry for Economic Affairs and Energy (BMWi), we investigate in this research project entitled "Long-term Scenarios for the Transformation of the Energy System in Germany III" how Germany can achieve its climate goals. For this research, we use our network of different models to calculate regionally and temporally highly resolved scenarios for achieving greenhouse gas neutrality (GN). An energy scenario describes a possible future development of the energy system within a set of parameters. However, our energy scenarios are not forecasts of future development, but rather represent consistent developments within the framework conditions applied. We aim to use our scenarios to explore the solution space for achieving greenhouse gas neutrality and to identify interdependencies. In doing so, we can identify robust strategies and necessary directional decisions. For the sake of transparency and to accompany the discussion, we will provide a variety of data and materials at the website www.langfristszenarien.de.

The decarbonisation of the energy system requires the use of climate-neutral energy sources. These can be either climate-neutral electricity, climate-neutral hydrogen or climate-neutral hydrocarbons. In a first step, we analyse three scenarios, each with a very pronounced use of one of these energy carriers, deliberately exploring the "corners" of the solution space. A number of other scenarios will follow in this project to shed further light into the solution space.

This report is a brief summary of these three greenhouse gas neutral scenarios and is intended as a written supplement to the Executive Summary slide set and the detailed project report.

The next section briefly outlines the three scenarios. Sections 3–6 present the individual energy demand sectors. Sections 4–7 look at energy supply and electricity grids. This report concludes in section 10 with an overview of the energy system in terms of energy flows, overall greenhouse gas emissions and costs.

2.2 Overview of the scenarios

The scenario worlds of electrification rely on a strong direct use of renewable electricity, although considerable amounts of hydrogen are also needed to achieve greenhouse gas neutrality even in these scenarios. The energy demand models each calculate scenarios with strong electricity use for their sector. Hydrogen is also needed here to a certain extent. The coverage of demand for electricity, heat in heat grids and hydrogen is optimised. The costs of the grids for electricity and gas are taken into account. The use of hydrocarbons is limited to the sustainable potential of biomass until 2050. The GN electricity scenario (GN-Electricity) presented here represents the base variant for further planned scenarios of the scenario worlds of electrification.

The scenario worlds based on hydrogen examine different characteristics of an increased use of hydrogen for the decarbonisation of the energy system. The GN-H_2-G scenario presented here analyses a very strong use of hydrogen in the energy system. The coverage of energy demand is optimised. In the modelling of the energy supply, the demand for hydrogen must be provided by electrolysis in Germany, Europe or other regions of the world, similar to the GN-Electricity scenario.

The scenario worlds based on synthetic hydrocarbons (Power-to-Gas/Power-to-Liquid (PtG/PtL)) examine the use of synthetic hydrocarbons (PtG/PtL) for the decarbonisation of the energy system. The GN-PtG/PtL scenario presented here relies on a very strong use of such synthetic hydrocarbons in the entire energy system. In addition to using the sustainable biomass potential, the required hydrocarbons are imported from regions outside of Europe.

3 Industry

For the industrial sector, a number of assumptions are identical in the three GN scenarios: In all three scenarios, the value added of the industrial sector grows by about 1% per year until 2050. The production volumes of energy-intensive basic materials develop at a relatively constant level or decline slightly until 2050. An important reason for the slight decline is the progress in efficient material use assumed for all scenarios along the value chains up to the end-use sectors such as the construction industry. Substantial progress in the use of secondary products, for example in steel or plastics production, was also assumed for the circular economy in all three scenarios.

However, the scenarios differ significantly with regard to the conversion of energy supply/demand according to the respective focal points (electricity, PtG, hydrogen). In the GN-Electricity scenario, direct electric solutions are preferred, which mainly refers to the conversion of process heat. Where this is not possible, e.g. because the energy carriers are used as materials, hydrogen is used (e.g. for the production of olefins). In the GN-PtG/PtL scenario, PtG (synthetic methane) is the preferred energy and material source in all applications. Only where other options have very high efficiency advantages, they complement the use of PtG (e.g. low-temperature heat via heat pumps). In the GN-H_2-G scenario, it is assumed that hydrogen will be available everywhere via a large-scale infrastructure by 2050. Hydrogen is the preferred energy carrier for energy as well as for material use.

The results show: By 2030, the scenarios achieve GHG reductions of 54% (GN-Electricity), 52% (GN-PtG/PtL) and 55% (GN-H_2-G), respectively, compared to the 279.2 Mt in 1990 in the industry sector. Thus, all three scenarios slightly exceed the sector target for industry in 2030 of 49 to 51% reduction.

The industrial sector achieves a GHG reduction of about 97% by 2050 compared to 1990. The picture is similar in the three GN scenarios. The remaining 7–8 Mt GHG emissions consist almost exclusively of process-related emissions. Although these will decrease continuously until 2050 due to process changes, material efficiency, innovative cement types and the use of CCU (CO_2 capture and utilisation), there will still be a significant base value of emissions, which is distributed over more than 20 individual source categories.

The energy consumption of the industrial sector considered here is made up of the final energy consumption according to the energy balances and the material use of energy sources in the chemical industry. In total, the energy consumption amounts to 850 TWh in 2015. In the course until 2050, the level and composition of the energy demand changes fundamentally in all GN scenarios.

In all three GN scenarios, energy consumption decreases continuously by about one fifth until 2050 (GN-Electricity: -23%, GN-PtG/PtL: -18%, GN-H_2-G: -21%). In all scenarios, this decline can be explained in particular by ambitious progress in energy and material efficiency as well as circular economy. In addition, in the GN-Electricity scenario, the electrification of processes is often accompanied by (final energy) efficiency gains, which explains the somewhat stronger decline in the GN-Electricity scenario. The system boundary also plays a role, in that the production of electrolysis hydrogen is accounted for in the conversion sector and not in industry.

Larger shifts can be seen in the importance of individual energy sources (Figure 1). In accordance with the overarching scenario guidelines, the scenarios develop very differently and show a strong shift towards electricity (GN-Electricity), PtG or synthetic methane (GN-PtG/PtL) or hydrogen (GN-H_2-G). A robust observation is therefore that for many applications different competing solutions exist.

In the TN-H_2-G scenario, the consumption of green hydrogen increases to a total of 360 TWh in 2050, accounting for about 52% of total energy consumption. At 41 TWh, the demand for hydrogen in 2030 is significantly lower, but still substantial. Driven by the conversion of the industrial plant stock, there is a relatively strong increase from 2030 to 2040.

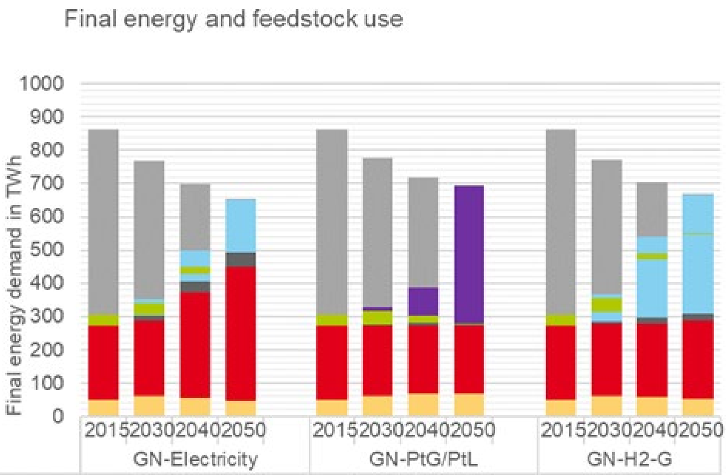
In the GN-PtG/PtL scenario, a less fundamental conversion is necessary, as industrial furnaces are normally already fired with natural gas (important exception: blast furnace). Accordingly, the speed of the conversion to PtG is mainly determined by the blending rate in the gas grid. In 2030, for example, there is only a demand for 12 TWh of PtG. In 2050, PtG is by far the most important energy source with 415 TWh or 60% of total energy consumption. Compared to today's consumption of natural gas (~240 TWh in 2015), this is a significant increase.

In the GN-Electricity scenario, electricity consumption almost doubles to 404 TWh in 2050. This makes electricity the most important energy source with a 62% share of total energy consumption. This increase is particularly due to the electrification of process heat across all industrial sectors. In addition, there is a strong increase in hydrogen demand to 156 TWh in 2050. This is used wherever direct electrification is not possible (e.g. because the energy carrier is used as a material) or because electrical processes are technically less advanced (i.e., steel production).

With regard to the regional distribution of electricity, gas and H_2 demand, large differences can be observed according to the German industrial structure. In the GN-Electricity scenario, electricity demand increases in almost all regions by 2050 compared to 2015, whereby in 70% of the regions, the increase even exceeds +50%. In the GN-H_2-G scenario, 49 regions each require more than 1 TWh of H_2 in 2050, with all regions having a certain minimum demand for H_2. In the GN-Electricity scenario, the H_2 demand is distributed among about 20 individual locations.

In the following figure, the sum of final energy use according to AGEB as well as material energy carrier use for ammonia and methanol/olefine production is shown.

Figure 1: Development of final energy demand incl. material use in the industrial sector



	GN-Electricity 2015	2030	2040	2050	GN-PtG/PtL 2015	2030	2040	2050	GN-H2-G 2015	2030	2040	2050
Fossil	558	418	201	1	558	448	333	0	558	404	165	1
Synthetic methane (feedstock)	0	0	0	0	0	2	18	115	0	0	0	0
Hydrogen (feedstock)	0	13	50	116	0	0	0	0	0	13	50	116
Synthetic methane	0	0	0	0	0	10	66	300	0	0	0	0
Biomass	30	33	20	1	30	41	21	1	30	42	16	1
Hydrogen	0	5	23	40	0	0	0	0	0	29	178	243
Ambient heat	0	13	34	43	0	5	9	4	0	7	17	19
Electricity	225	228	318	404	225	211	206	205	225	217	219	235
Derived heat	48	61	54	46	48	61	66	68	48	60	60	53

Key to the success of the transformation is the conversion to CO_2-neutral production processes in the steel, chemical and cement/lime sectors, due to their currently very high CO_2 emissions. In all three sectors, far-reaching changes in production routes are implemented in the GN scenarios. In steel production, the current blast furnace route is completely replaced by the direct reduction of iron ore using H_2/PtG as the new primary route. In cement production, there will be a switch to electric kilns, new low-CO_2 binders and CO_2 capture. In basic chemicals, the production of olefins for further plastics production is converted to H_2 or PtG as a new raw material. In the GN-Electricity and GN-H_2-G scenarios, remaining CO_2 emissions from cement and lime production are captured to be used for the production of olefins (CCU). In the GN-PtG/PtL scenario, captured emissions from cement production are stored (CCS).

All these conversions are associated with extensive plant replacements and new investments that go well beyond what is currently observable. Many of the necessary technologies are still available only on the demonstration scale and are not yet economically viable under the current boundary conditions. Especially the extensive use of CO_2-neutral secondary energy sources leads to a strong increase in costs.

The transformation towards an almost CO_2-neutral industrial production requires fundamental decisions with regards to course-setting. Some important prerequisites are for all three scenarios:

- Availability of new CO_2-neutral manufacturing processes marketable and upscalable to industrial scale from 2025/2030 onwards. Achievement of 100% stock diffusion by 2050 in the basic material sectors, especially in the chemical, steel and cement industries.
- Availability of green electricity, hydrogen or PtG on a large scale and complete displacement of fossil energy sources.
- Changed decision-making behaviour favours the necessary speed of conversion, especially with regard to the evaluation of investments in CO_2-neutral technologies.
- Green hydrogen or PtG supply the chemical and steel industries.
- The concept of circular economy continues to gain acceptance: Electric steel is used for quality steels, stronger plastic recycling.
- Significant increases in material efficiency along the value chain, especially in the construction industry.
- Energy efficiency continues to be ambitiously increased and existing potentials are exploited using the best available technologies.
- CO_2 becomes a raw material and a CO_2 cycle is established over the plastics life cycle, including infrastructure for capture and transport (exception TN-PtG/PtL: here CO_2 capture and storage instead of CCU).
- The conversion and expansion of the transport infrastructure for hydrogen and electricity takes place over a large area and quickly, so that it does not become a bottleneck of the industrial transformation even in heavily transition-affected regions (exception TN-PtG/PtL scenario).

Furthermore, the scenarios also show some differences. The GN-PtG/PtL scenario shows a lower need for conversion of existing industrial plants and transport infrastructure. On the other hand, energy use is completely switched to a very expensive energy source. In the steel and chemical sectors, extensive conversions to new CO_2-neutral processes is also necessary in the PtG/PtL scenario.

The GN-H2-G scenario requires a fundamental and very comprehensive expansion of the H2 transport infrastructure, especially down to the distribution level. The required conversion of existing plants is more extensive than in the TN-PtG/PtL scenario, since the conversion to hydrogen requires, for example, the replacement of a large number of industrial furnaces and steam boilers.

The GN-Electricity scenario shows an even more profound and comprehensive conversion of the industrial plant fleet. Electrification of furnaces and steam generators is likely to involve a replacement of equipment in most cases. Requirements for the transport infrastructure are considerable. However, for hydrogen transport, a transport network supplying about 20 large industrial sites is sufficient. A supply of hydrogen at the distribution level is not necessary. In the case of the electricity grid, it is particularly important to avoid local bottlenecks that may surge due to a sharp increase in electricity demand from individual large industrial plants.

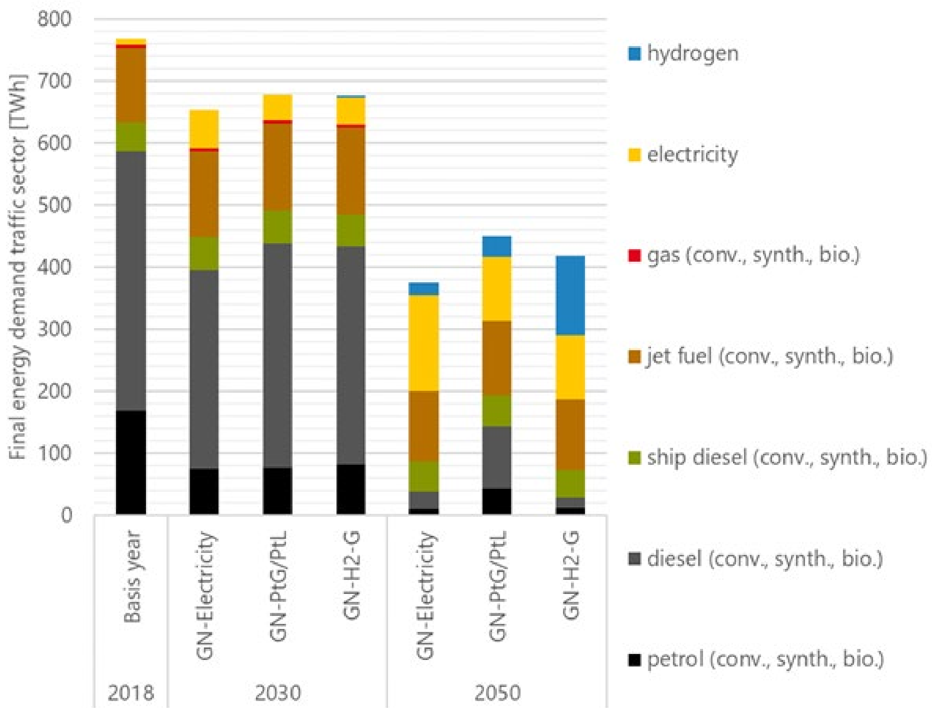
4 Traffic and transport

In the project Long-term Scenarios III, the final energy demand in the transport sector is calculated with the the two models ASTRA (www.astra-model.eu) and ALADIN (www.aladin-model.eu). The transport demand for ground-based transport is determined with the System Dynamics model ASTRA. ALADIN, as an agent-based model, then simulates the purchase process and the decision for or against a particular drivetrain.

4.1 Overview final energy demand in the traffic sector

The final energy demand in transport decreases significantly in all three scenarios, primarily due to more efficient drivetrain alternatives and efficiency improvements in conventional combustion engines. While transport demand grows in freight transport, a slight decline of the traffic volume in the passenger car sector also contributes to the reduction. The greatest reduction of 52% is achieved in the GN-Electricity scenario due to the high efficiency of electric drives. In the GN-H_2-G scenario, the final energy demand is reduced by 45%, in the GN-PtG/PtL scenario by 42%. Figure 2 shows the final energy demand in the transport sector for all scenarios for 2030 and 2050. In 2050, the final energy demand is covered by electricity and BtL/PtL fuels in all scenarios, and by hydrogen in the GN-H_2-G scenario.

Figure 2: Final energy demand in the traffic sector by energy carriers



4.2 Development of individual modes of transport

Depending on the scenario, final energy demand in 2050 in the passenger car transport is reduced by 62% (GN-PtG/PtL), 66% (GN-H_2-G) and 72% (GN-Electricity) compared to 2018. In all scenarios, the reduction in final energy demand is mainly due to the electrification of the fleet and ambitious efficiency improvements. In the GN-Electricity scenario, in the long term this involves almost exclusively purely battery-electric vehicles (78% of the fleet). The share of electric vehicles, including plug-in hybrids, is 88% in 2050. In the GN-H_2-G scenario, the share is 62%. In addition, a quarter of the fleet consists of fuel cell vehicles. In the other scenarios, fuel cell vehicles are only available in small numbers. They are particularly suitable for long-distance drivers, but compete with plug-in hybrids. Due to the small hydrogen demand, it is unclear whether the H_2 infrastructure and the vehicles would actually be realised in the GN-Electricity and GN-PtG/PtL scenarios. In the GN-Electricity and TN-H_2-G scenarios, no new petrol or diesel vehicles are registered in 2050, but small residual stocks remain. In the GN-PtG/PtL scenario, their share of the stock is 45% in 2050. These are primarily vehicles with lower mileage, for which the higher purchase prices of alternative drives do not pay off. In the GN-PtG/PtL scenario, electric vehicles are the most widespread form of propulsion, accounting for 52% of the fleet. Thus, electric drives dominate in passenger cars even with strong variation of the framework parameters.

For light and medium commercial vehicles, almost complete electrification takes place in the long term in all scenarios. High but constant mileages make the battery-electric drives, which are cheaper in terms of running costs, more economical than the diesel vehicles, which are cheaper in terms of investment. By 2030, the number of battery-electric light and medium commercial vehicles will increase to approx. 14%. By 2050, the share rises to at least 96% in all scenarios. Fuel cell electric vehicles are used for niche applications, such as very long ranges. However, their role depends on whether the vehicles can also be made available economically in small numbers.

In the case of heavy commercial vehicles, the scenarios differ significantly. Here, the running costs are decisive for the economic viability of the vehicles, due to the high mileage. Therefore, in all scenarios, the part of the fleet that can be electrified without additional public charging infrastructure – about one third of the fleet under the assumptions made – will be converted to battery electric vehicles by 2050. Depending on the scenario and the associated infrastructure, the remaining fleet is converted to (hybrid) trolley vehicles in the GN-Electricity scenario and fuel cell electric vehicles in the GN-H_2-G scenario. The overhead lines in the GN-Electricity scenario is representative for a public charging infrastructure and can possibly be expanded or replaced by fast charging stations. In the GN-PtG/PtL scenario, diesel vehicles and partly fuel cell electric vehicles are used.

Depending on the scenario, the reduction in final energy demand for commercial vehicles by 2050 is 41% (GN-PtG/PtL), 44% (GN-H_2-G) or 54% (GN-Electricity).

In all scenarios, air transport and shipping only use alternative propulsion systems to a small extent, primarily on short-haul routes and in inland shipping. Depending on the scenario, 160 to 170 TWh of biogenic or synthetic fuels will have to be made available in 2050, mainly for international aviation and shipping, despite high assumed efficiency improvements. The assumed increase in transport volume is the decisive driver for this.

Bus and rail transport play a subordinate role in terms of energy demand.

4.3 Key conclusions for the traffic sector

The scenarios presented here span a possible solution space for the decarbonisation of the transport sector. At the same time, key conclusions can be derived from the scenario comparison.

In the case of passenger cars, the conversion of large parts of the fleet to battery-electric vehicles seems certain from today's perspective. The creation of appropriate framework conditions, for example charging infrastructure, financial purchase incentives or access restrictions in cities, makes therefore sense in order to accelerate the conversion, if necessary.

Direct electrification should be made possible and accelerated for light and medium commercial vehicles. The same applies to a significant proportion of heavy commercial vehicles. Electricity, hydrogen or biogenic/synthetic fuel can be used in future, especially for long-distance transport. Here, the respective advantages and disadvantages should be further analysed and then, due to the large leverage effect, infrastructure development should be initiated quickly.

For ships and aircrafts, alternatives such as BtL and PtL with favourable abatement costs should be further researched in order to ensure their long-term operation. Alternative propulsion systems, for example battery or fuel cell aircrafts are being researched, but are still at the beginning of their development. Their contribution to decarbonisation of the traffic sector and their role in the future energy system is therefore very uncertain.

5 Building sector

The building sector is defined according to the systematics of the German Climate Protection Act, i.e. it includes both the buildings of private households as well as trade, commerce and services. The final energy consumption for space heating and cooling, hot water and auxiliary energy is accounted for.

In the building sector, the GN-Electricity scenario has the highest efficiency. The requirements for insulation layers in new buildings and renovations increase by 27% on average. The renovation cycles for façades, roofs, basements and windows are accelerated by an average of 20%. All refurbishments are carried out using the coupling principle when maintenance measures are due anyway. The minimum insulation requirements are met in 97% of the renovations. Up to 30% of those even exceed these numbers. In 2050, 37% of the buildings will have ventilation systems with heat recovery. Final energy consumption (including environmental energy) is reduced by 47% by 2050 compared to 2008.

The use of fossil fuels in buildings will decrease to zero by 2050. Synthetic energy sources are excluded by definition for use in buildings. From 2030, no more boilers for oil or gas will be installed, so that they will be phased out by 2050 and only a few systems will have to be decommissioned before the end of their useful life. The stock of heat pumps grows in this scenario from about 1 million units in 2020 to 5.8 million in 2030. Total electricity consumption for space heating and hot water increases from 41 to 100 TWh in the scenario. The increase is dampened by the reduction of direct electricity heating and water heaters by 26 TWh. Restrictions for heat pumps exist especially in areas with dense development. These areas are in any case very well suited for supply with local or district heating. In this scenario, heat pumps and heat grids complement each other in terms of regional distribution.

The number of buildings supplied via a heating network increases by a factor of 2.4 to 4.4 million buildings. The number of wood pellet boilers also increases by a factor of 2.6. Solar thermal systems only make a small contribution in this scenario. This is also due to the fact that solar thermal in combination with heat pumps as the main heat generator is less economical, as the operational heat supply costs for heat pumps are low.

The GN-PtG/PtL scenario is characterised in the building sector by direct combustion of synthetic methane (PtG) in boilers and by only a slight improvement in building efficiency through insulation measures. The requirements for the insulation of the building envelope are raised by an average of 15% and thus fall short of the current level of an Efficiency House 55.97% of the renovations carried out comply with the legal requirements. Of these, a further 20% exceed the minimum level. The service life of the building components remains at the current level. By 2050, 21% of the buildings in this scenario are equipped with a ventilation system with heat recovery. Final energy consumption is reduced by 33% compared to 2008. Fossil fuel oil is no longer used in 2050. Boilers for liquid synthetic energy sources (PtL) are also not in the stock. Methane remains the energy source with the highest single share of energy consumption – initially as natural gas, later as synthetic methane (PtG). Adaptations in the buildings are not necessary for the switch to PtG. In 2050, 37% of heat generators are gas boilers. The stock of heat pumps grows to 36% by 2050. The number of heat grid connections increases by a factor of 2.2. Wood pellet boilers increase by a factor of 2.7 compared to 2018. Solar thermal systems are economically attractive in combination with gas heating – especially with high PtG prices. Their contribution increases to 15 TWh in 2050.

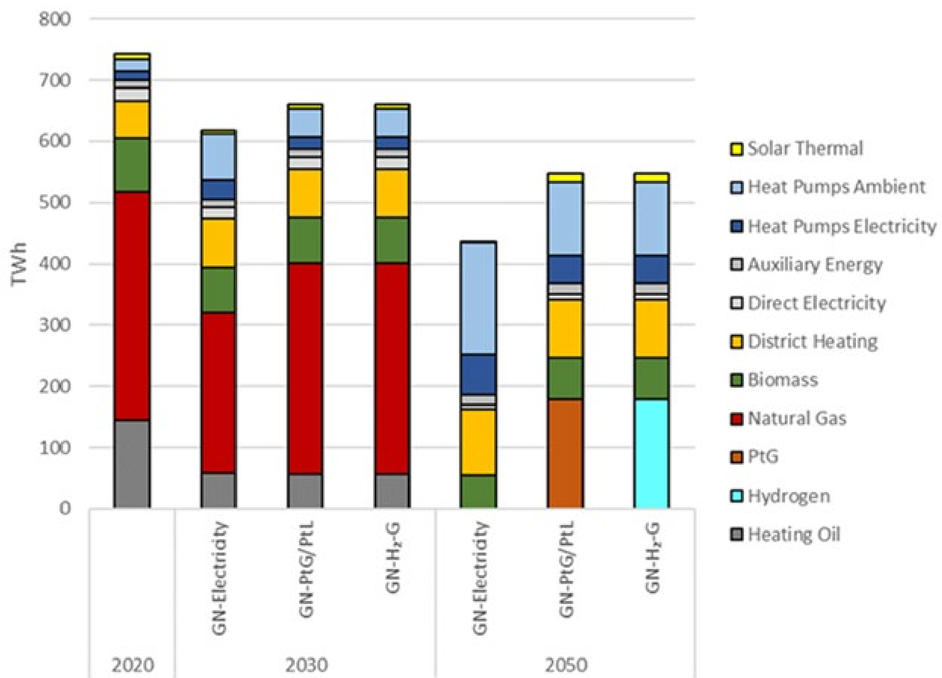
Direct GHG emissions attributable to the building sector decrease to 85 Mt by 2030. At this point, PtG is not yet available for building heat. The climate target for 2030 is not met.

In the GN-H_2-G scenario, hydrogen generates a high proportion of space heating and hot water. It is burned directly in boilers. Fuel cells are not used. They are examined in a separate scenario. In the building sector, the developments of the GN-PtG/PtL scenario are adopted without changes and hydrogen is used instead of synthetic methane. This allows the differences between the two supply options to be compared directly. Final energy consumption for space heating and hot water decreases by 33% compared to 2008. Gases remain the energy carriers with the highest single share of energy consumption – initially as natural gas, later as hydrogen. The conversion assumes that a hydrogen admixture of up to 10% is possible without technical measures in the buildings. For higher hydrogen shares, boilers and fittings must be replaced. Due to the effort involved, it is assumed that the conversion to 100% hydrogen will take place in one stage and that there will be no admixtures between 10 and 100%. In 2050, all gas boilers will run on hydrogen. The shares of heat pumps, heat grids, wood boilers and solar thermal systems are taken over unchanged from the GN-PtG/PtL scenario.

Direct GHG emissions fall to 85 Mt by 2030. The climate target for 2030 is not met.

The total sum of emissions in the GN-PtG/PtL and GN-H_2-G scenarios in the period from 2021 to 2050 is 33 per cent higher than in the GN-Electricity scenario.

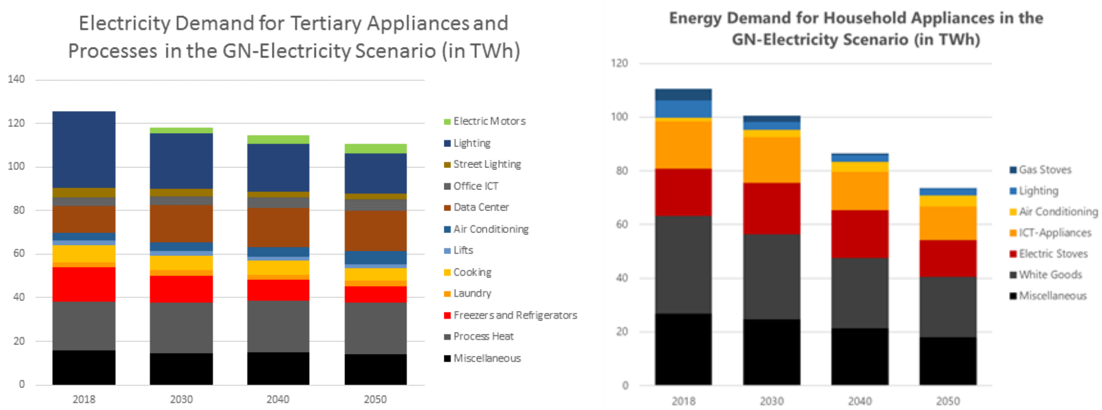
Figure 3: Energy demand in buildings



6 Household Appliances and Tertiary Processes and Appliances

The energy demand of processes and appliances in the tertiary sector and of household appliances was calculated with the FORECAST energy demand model. In the tertiary and domestic sectors, only the GN-Electricity scenario was calculated, since even with a strong focus, H_2 and PtG/PtL could only play a minor role in the long term.

Figure 4: Energy demand from tertiary processes and appliances



In the tertiary sector, the share of fossil energy sources decreases steadily in the GN-Electricity scenario and reaches zero by 2050. A large part of the appliances and processes can be electrified. For individual processes and appliances, GHG-neutral alternatives (biofuels, local and district heating & solar thermal) remain more cost-effective than electrification, so that they still cover 12% of the total energy demand in the tertiary sector in 2050. In the household sector, gas cookers are currently the only non-electricity-based appliances. They could be completely converted to electric cookers by 2050. In both sectors, significant savings are possible through efficiency gains. Nevertheless, we observe increasing overall energy consumption of certain appliances and processes, especially in data centres, ICT devices and air conditioning.

Through extensive electrification and efficiency gains in the GN-Electricity scenario, the electricity demand of the tertiary sector is reduced by 12% and in the residential sector by 31% compared to the base year 2018. The total energy demand in the GT-Electricity scenario decreases by 30% in the tertiary sector and by 33% in the residential sector between 2018 and 2050.

The development of the energy demand of data centres, as well as the energy demand of ICT devices and air conditioning in households and the tertiary sector is subject to greater uncertainties regarding the order of magnitude. Nevertheless, the trend clearly shows that the number of ICT and air conditioning devices is and will be increasing, while the number of other devices is stagnating. The energy demand in data centres is also steadily increasing, so that this must be offset by a significant reduction of other appliances and processes to achieve a reduction in energy demand in the tertiary sector. Increased electrification can make an important contribution to this.

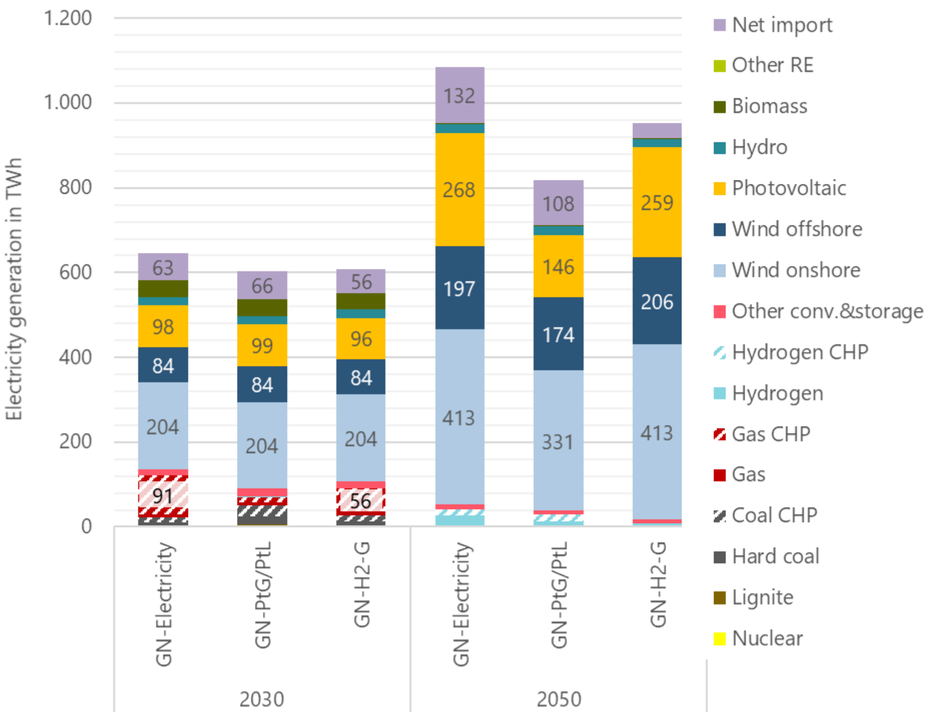
7 Energy supply

Within the scope of this project, the coverage of energy demand with certain boundary conditions is calculated simultaneously for the energy systems of electricity, heat grids and hydrogen. This calculation was carried out with the help of the energy system optimisation model Enertile.

7.1 Electricity sector

As the option of decarbonisation via electricity use becomes robustly established in many applications, electricity demand increases significantly by 2050 in all scenarios. In the GN-Electricity scenario, net electricity generation including net electricity imports is slightly above 1050 TWh. In the GN-PtG/PtL scenario, it is significantly lower at around 800 TWh. In terms of generation volume, onshore wind energy is the most important technology in Germany in all three scenarios, followed by PV and offshore wind energy. The potentials of onshore technologies are exploited to a very large extent, especially in the GN-Electricity scenario and the GN-H_2-G scenario. It should be mentioned here that a minimum electricity generation from renewable energies of 900 TWh is specified for the year 2050 in the GN-Electricity and GN-H_2-G scenarios. In the GN-PtG/PtL scenario, the figure is 650 TWh. Without such a requirement, Germany would import larger amounts of electricity. The largest electricity imports take place in the GN-Electricity scenario with 132 TWh and in the GN-PtG/PtL scenario with 108 TWh. Other important targets in this scenario are a minimum capacity of 20 GW of offshore wind energy in 2030 and 40 GW in 2040. In addition, a minimum target of 100 GW of PV applies in this scenario from 2030. The expansion targets of at least 5 GW and 10 GW of electrolysis are also specified. The figure clearly shows that even in the GN-PtG/PtL scenario, no methane is used in electricity generation in 2050. In this case, hydrogen is the cheaper energy carrier to provide power in a few hours with a low feed-in of renewable energies.

Figure 5: Electricity generation in Germany

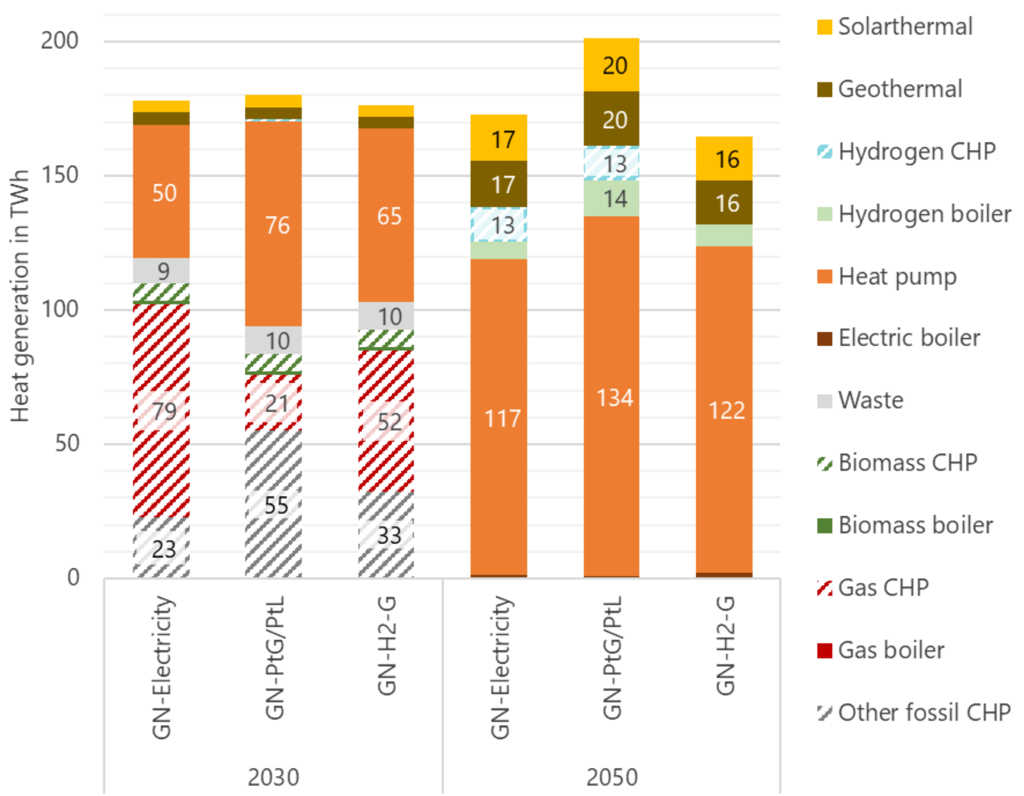


In total, this scenario is characterized by a very high land need for the extension of renewable energies with corresponding potentially high land use pressures or competition.

7.2 Heat grids

In addition to the electricity system, the heat grids are also undergoing a fundamental transformation. Large heat pumps provide a significant and increasing proportion of the energy in all three decades. In the calculations here, they are modelled as air-source heat pumps whose efficiency depends on outdoor temperatures. In reality, other heat sources such as rivers, industrial sites or waste heat could increase the efficiency locally. Since the industry is undergoing a fundamental transformation in the scenarios, industrial waste heat was not integrated here to meet heat demand. The same applies to waste incineration, which is accounted for in terms of output and costs. But due to the energy demand of the CO_2 capture used in 2050, we have refrained from balancing a contribution to heat production in the spirit of prudence. In the GN-Electricity and GN-PtG/PtL scenarios, the energetic role of CHP decreases significantly by 2050. In the GN-Electricity and GN-PtG/PtL scenarios, hydrogen CHP generates approx. 13 TWh. Hydrogen boilers serve to cover the peak load in times of low feed-in of renewable energies in the power system. The expansion of geothermal and solar thermal energy was specified exogenously here on the basis of a potential analysis. Not shown here is the great importance of heat storage in all scenarios. Here, a significant expansion is taking place in order to react to the fluctuating feed-in of renewable energies.

Figure 6: Supply of the heat demand in heat grids



7.3 Hydrogen system

In all scenarios, hydrogen is used to a small extent in the electricity system as a back-up. Depending on the scenario, there is additional demand for hydrogen from the other sectors such as industry and transport and possibly buildings. In our modelling, hydrogen can be produced in Germany as well as imported from Europe and other regions of the world, e.g. the MENA region. In the GN-Electricity scenario, 170 TWh are imported from Europe to Germany. In the GN-H_2-G scenario, this amounts to 510 TWh. An import from other regions of the world is not competitive in the parameterisation of the scenarios. The potentials of renewable energies in Europe are highly utilised in all of the scenarios. If such extensive land use for energy generation is not possible in Europe and the uncertain transport costs for hydrogen are lower, importing hydrogen from other regions of the world could finally be competitive. Regionally, generation and reconversion are distributed differently in the electricity system. In Germany, electrolysis is concentrated in the north in all scenarios. In Europe, a large part of the capacity is located on the British Isles, in northern Europe and on the Iberian Peninsula. The re-conversion of hydrogen into electricity in Germany takes place increasingly in the west and south.

7.4 Sector coupling

The Enertile model calculates the use of technologies in the electricity system, the heating system and the hydrogen system on an hourly basis. In the modelling, a very efficient market-driven sector coupling takes place. Ultimately, the choice of technologies and their use are strongly oriented towards the fluctuations in electricity generation from renewable energies. Through supra-regional electricity trading, the absorption of electricity in the heating grids including heat storage as well as hydrogen as a backup, no further electricity storage facilities (i.e., batteries) are added to the system in Germany. This solution shows the enormous potential for the integration of renewable energies, if efficient regulation including the technical prerequisites for sector coupling can be created.

8 Electricity grids

The optimisation of the energy supply by means of Enertile also takes electricity grids into ac-count. The result of the Enertile thus represents the cost-optimal match of supply and demand, also considering the associated costs for the expansion of electricity transmission and distri-bution grids. The grid expansion requirements for Germany are also assessed in detail in separate models.

8.1 Transmission grid

Each of the three scenarios requires a considerable grid expansion in the German transmission grid by 2050, which is also cost-optimal for the energy system as a whole in terms of optimising the energy supply. A minimum amount of grid expansion to be considered in all scenarios was specified. This comprises the expansion of the German transmission grid currently provided for in the Energieleitungsausbaugesetz (EnLAG, "Energy Line Expansion Act" and the Bundesbedarf-splangesetz (BBPlG) and amounts to approx. 18,700 kilometres of electric circuits, which will be upgraded or expanded by 2030 compared to today (current grid as of 2020). In addition, depend-ing on the scenario, a further 15,100 km (GN-PtG/PtL) to 21,300 km (GN-Electricity) of expansion and reinforcement measures will be required. In addition to the expansion of power lines, phase-shifting transformers and grid boosters will be used and added (rather moderately overall).

As a result of the expansion and reinforcement measures, the costs of the transmission grid will also increase. In this project, it was assumed as a general rule that 40% of the extended or reinforced line kilometres will be implemented as underground cables at correspondingly higher costs compared to overhead lines and thus also the majority of the existing network. Therefore, the grid costs increase more than the grid lengths. The annuity costs of the German transmission grid will rise from approx. 1.3 billion EUR/a today to 5.5 billion EUR/a (GN-Electricity), 4.4 billion EUR/a (GN-H2-G) and 3.9 billion EUR/a (GN PtG/PtL) in 2050.

The decisive factor for grid expansion is not only the increasing demand for electricity transport from the RE generation centres to the load centres within Germany, but also the significantly increased integration of Germany into the European electricity transmission-grid compared to today. Thus, Germany's cross-border exchange capacities will increase to around 80–100 GW by 2050, which is roughly three times as much as today. The additional exchange capacities are not only needed for imports to or exports from Germany. In part, they also serve as transit capacities for very large-scale European electricity exchange.

The expansion of the electricity transmission grid is an important component in all scenarios examined and allows the overall costs of the energy system to be reduced. The additional need for grid expansion and reinforcement in Germany is considerable, but remains in the order of magnitude of the grid expansion planned today for the period 2030 to 2050. The likewise extensive European electricity grid expansion requires an early, European-coordinated approach.

8.2 Distribution grid

The electricity distribution grids also have considerably to be expanded in order to accommodate the increasing RE generation and to supply the increasing electricity demand. In all three scenarios, accordingly the annualised costs of the distribution grids significantly increase. In the GN-H2-G and GN-Electricity scenarios, the annualised costs roughly double by 2050 compared to today (13.4 billion EUR/a or 15.4 billion EUR/a in 2050 compared to approx. 7.5 billion EUR/a today). Due to the lower RE expansion and the less strongly increasing peak load, the increase in the GN-PtG/PtL scenario is lower (11.8 bn EUR/a in 2050).

The "dynamic capping" of RE generation assumed in the modelling is an effective and efficient measure to reduce grid-expansion demand. This form of capping of generation peaks of RE plants takes into account that it is not the feed-in of an individual plant that is decisive for grid expansion, but the generation in the overall collective of a grid area. From the analyses, it can also be concluded that it makes sense to use the largest possible diameter for all lines that are replaced in the future, since the diameter is decisive for the capacity of the grid, but the costs arise primarily from the underground work, which are independent of the diameter.

9 Gas grids

9.1 Long distance transmission grid

In all GN scenarios, there is a hydrogen transport network, the scope of which depends on hydrogen penetration, and a declining network demand for methane transport. In all scenarios, the separate hydrogen transport network is primarily developed from converted natural gas pipelines.

The transport network topologies follow the same development path in the GN-Electricity and GN-H_2-G scenarios until 2040. With a methane network of 25,430 km in length (26,250 km in 2030) and a hydrogen network of 7,210 km in length (4,850 km in 2030). In 2050, the hydrogen network is more extensive in the GN-H_2-G scenario (10,200 km to 32,000 km depending on the extent of hydrogen use in the heat sector) than in the GN-Electricity scenario (7,210 km). In both scenarios, the methane network is completely shut down by 2050. This is due to the scenario assumptions and a phase-out of natural gas. In the GN-PtG/PtL scenario, a hydrogen network with a length of 2,880 km is sufficient from 2030. In the methane network with a length of 29,750 km, which is slightly reduced compared to the current network, only synthetic methane is transported.

The annuity costs for grid operation increase in all GN scenarios due to variable operating costs for hydrogen transport that are up to four times higher than for methane transport. In the base year, the costs amount to € 590 million /a. In 2050, they amount to between 600 million € /a and 1,460 million € /a. In addition, between 2 million € /a and 160 million € /a are incurred annually in the scenarios for securing the financing of the decommissioning. This sum is necessary to be able to finance all cumulative decommissioning costs in 2050. In addition, annual costs of between 130 million € /a and 1,300 million € /a must be taken into account for the conversion of the methane transport network to hydrogen transport.

9.2 Distribution grids

The gas distribution network infrastructure is in decline in all GN scenarios compared to the current network with 482,500 km and 44,800 gas pressure reduction and metering stations (PRMS). The continued operation of the gas distribution networks is given to a reduced extent in the GN-H_2-G and GN-PtG/PtL scenarios in 2050. In the GN-Electricity scenario, there is a complete shutdown of the gas distribution grids. In all scenarios, this development is due to the declining use of gas for decentralised building heat.

From 2030 onwards, the path differences between the GN scenarios become visible. In the GN-Electricity scenario, there is already a stronger decline in the required gas distribution network infrastructure. This continues increasingly in the following support years. The differences between the GN-PtG/PtL and GN-H_2-G scenarios are smaller. At the high-pressure level in the GN-H_2-G scenario, there is a lower network demand in the long term. This is due to a connection of industry to the transport grid level or a switch to other energy sources. In addition, from the base year 2040 onwards, a conversion of grid areas to hydrogen is part of the transformation of the gas distribution grids. Although the conversion has hardly any influence on the necessary network length, it does have an impact on the costs due to the upgrading processes.

The annuity costs for network operation also decrease in all GN scenarios. They decrease from €3.3 billion in the base year to between €0 and €2 billion in 2050. The lower annuity operating costs are due to the lower required gas distribution network infrastructure. In addition, between 160–540 million € /a and 320–1,120 million € /a are incurred annually in the scenarios to ensure the financing of the decommissioning. In the case of the GN-H_2-G scenario, annual costs of between 410 and

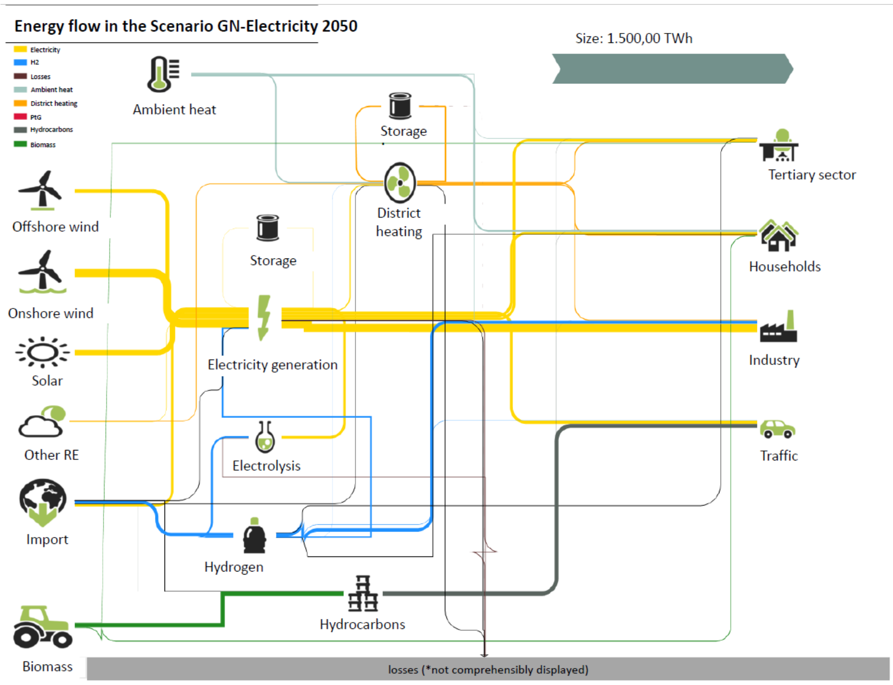
2,200 million € /a must also be taken into account for the rededication of the distribution grids. Compared to the transmission grid, the costs for decommissioning and reallocation may be lower due to the smaller line diameters, which is why a lower and upper estimate is given.

10 Integrated system perspective

10.1 Overview of the energy system

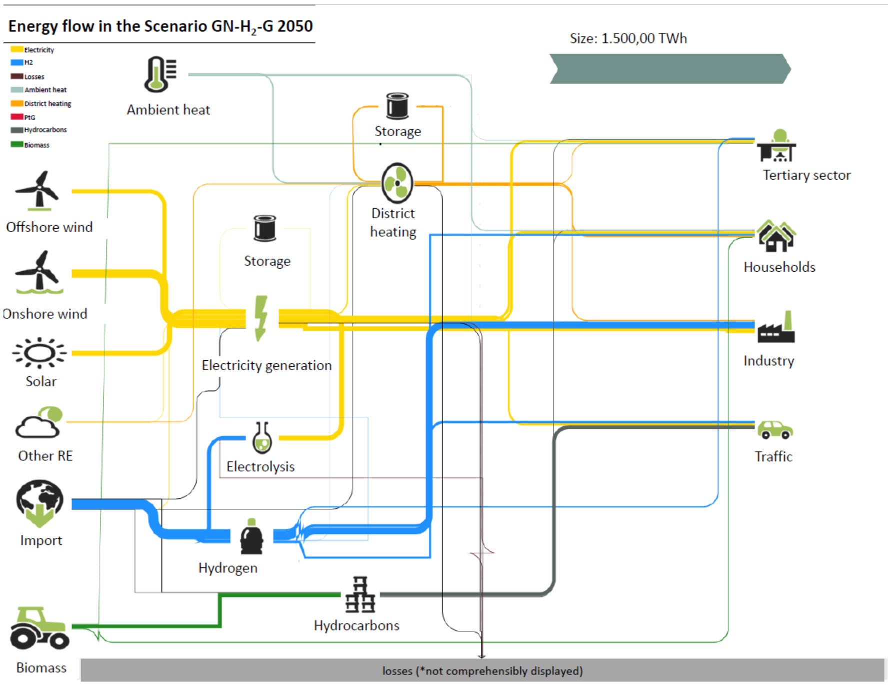
The following diagram shows the major energy flows of the energy system for the scenario GN-Electricity in 2050. Although electricity consumption increases significantly in absolute terms, direct electric applications usually have very high efficiency levels (for example, there is no conversion of electricity into other energy sources), which is why it does not increase so much in relative terms. Furthermore, in this scenario, a lot is invested in efficiency, and a large part of the electricity is generated by renewable energies in Germany, as specified. 132 TWh of electricity and 170 TWh of hydrogen are imported. Since both energy sources are ultimately produced by electricity from renewable energies, an import of 375 TWh electricity equivalents can be roughly calculated.

Figure 7: Energy flow diagram Scenario GN-Electricity 2050



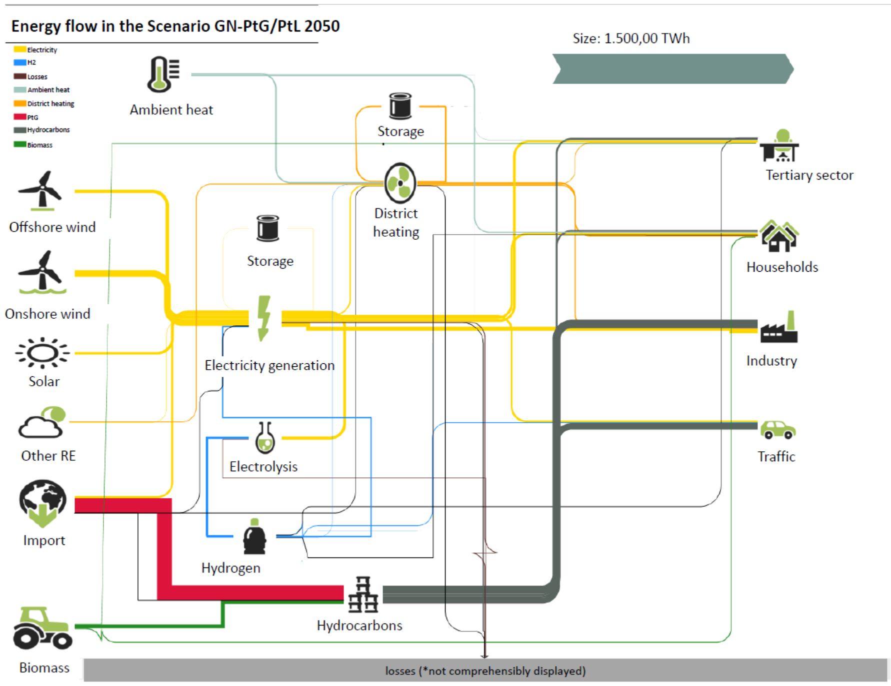
The central assumption in the GN-H_2-G scenario is the emergence of a relevant hydrogen sector (production, distribution and consumption). As a result, the energy system is dominated by the electricity and hydrogen sectors. Hydrogen mainly replaces fossil fuels (fuel switch). On the supply side, there is a further expansion of renewable energies and the development of electrolysers in Germany and Europe. The fact that Germany cannot cover its own hydrogen demand means that large import volumes will be generated by a European hydrogen network. Exports from the MENA region or other regions of the world only play a role under certain circumstances. On the demand side, a conversion is taking place in the areas of industry (heat), transport (fuel cells) and buildings (hydrogen heating). This places high demands on the hydrogen supply infrastructure as well as on private investments in corresponding systems. In this scenario, approx. 510 TWh of hydrogen and 34 TWh of electricity are imported. This corresponds to 760 TWh of electricity equivalents.

Figure 8: Energy flow diagram Scenario GN-H_2-G 2050



The following illustration shows the major energy flows of the energy system for the GN-PtG/PtL scenario in 2050. Hydrocarbons remain the central energy source of the energy system and are used in particular in industry and transport. In this scenario, 107 TWh of electricity and 750 TWh of synthetic hydrocarbons are imported. An import of hydrogen is not envisaged in this scenario. Due to the high conversion losses in the production of synthetic hydrocarbons, a total of 1600 TWh of electricity equivalents are imported. In particular, the land use for production abroad is not insignificant. In a rough calculation, the production of imported hydrocarbons in Algeria with PV would require an area of at least 18,000 km². In addition, there would be further areas for capturing CO_2 from the air.

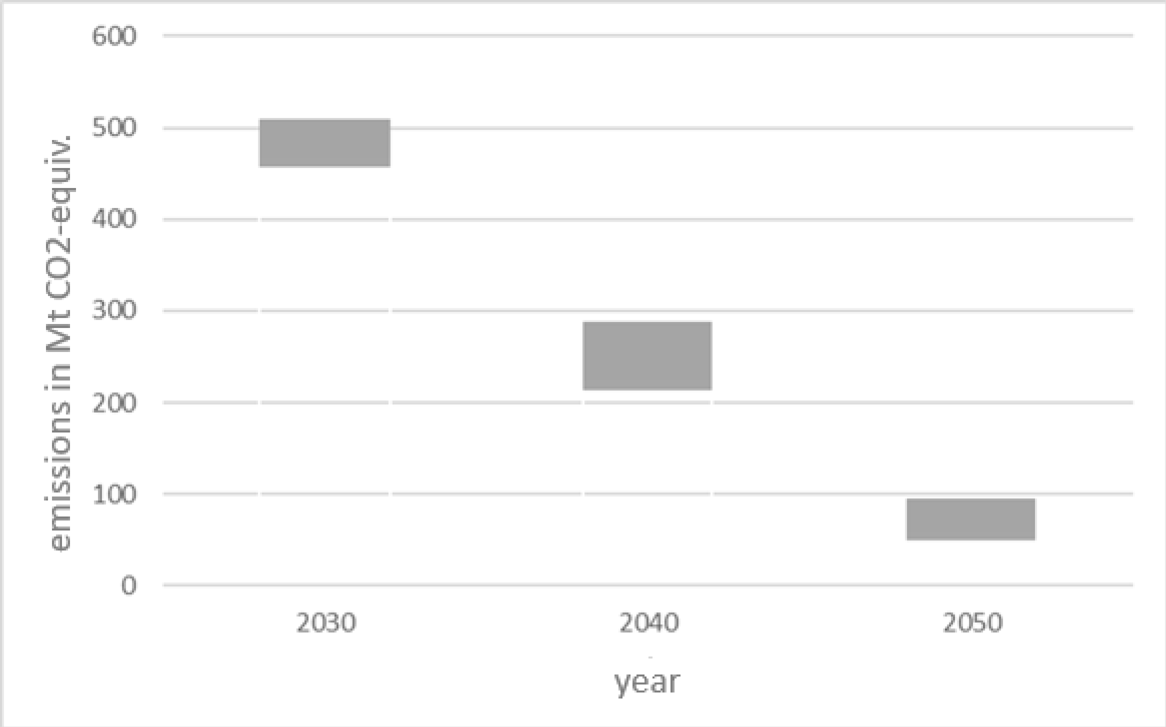
Figure 9: Energy flow diagram Scenario GN-PtG/PtL 2050



10.2 Greenhouse gas reduction

The following figure shows the development of greenhouse gas emissions in the range of scenarios. The detailed balancing of agriculture has not yet been fully completed. For this reason, the values shown contain additional safety margins upwards and downwards. The development of emissions is comparable in all scenarios. In all scenarios, greenhouse gas emissions are reduced by more than 60% by 2030 compared to 1990, including international air transport. By 2050, emissions will fall to the order of 70 Mt. These residual emissions must be compensated by negative emissions. This can be done, for example, through further changes in land use or CO_2 capture from the air. In view of the considerable effort required to reduce emissions in these scenarios, it is clear that the issue of negative emissions must also be addressed early on for Germany to achieve true greenhouse gas neutrality.

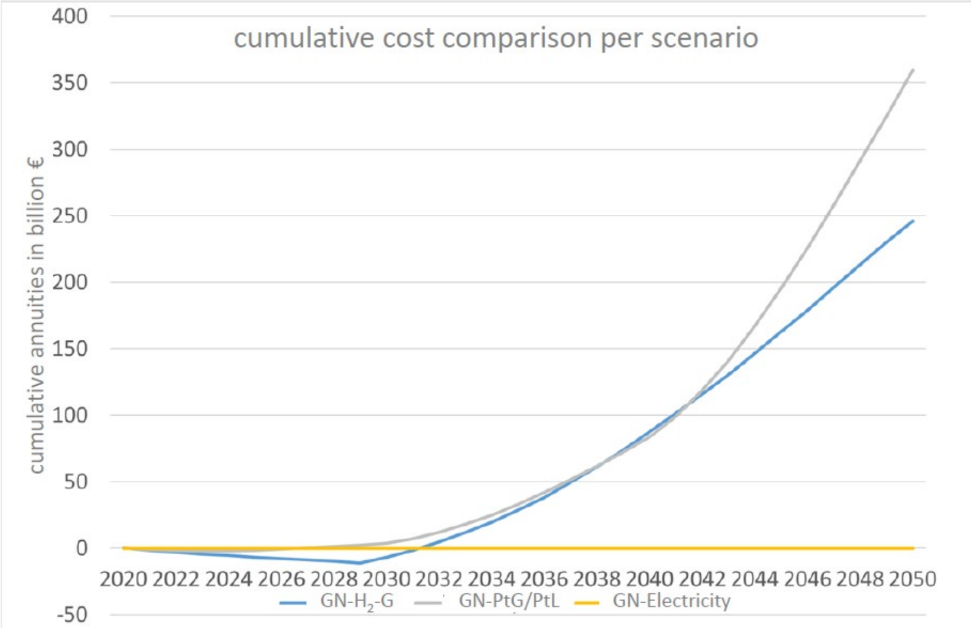
Figure 10: Development of the greenhouse gas emissions in Mt



10.3 Cost

The calculation of costs is not the focus of this study. Nevertheless, the model network makes it possible to show costs. Within the framework of the study, a uniform economic interest rate of 2% is used as the basis for calculating the costs of the scenarios in all sectors. The comparison of the scenarios is of particular interest. The figure shows the cumulative difference in the costs of the GN-H_2-G and GN-PtG/PtL scenarios compared to the most favourable scenario GN-Electricity. It shows that the GN-PtG/PtL scenario is more than 350 billion € more expensive than the G-Electricity scenario by 2050. The GN-H_2-G scenario costs about €250 billion more by 2050. The main reason for the higher costs are the higher fuel costs. Synthetic hydrocarbons are a more expensive fuel than electricity in this scenario, despite very optimistic assumptions. In terms of energy services, this also applies to hydrogen in a somewhat weakened form. The scenarios differ not only in the absolute level of costs, but also in the use of the money. In the GN-Electricity scenario, significantly less money flows into the energy carriers, but considerably more money into infrastructure and the shell of buildings. In the GN-PtG/PtL scenario, significantly less money flows into infrastructures and buildings but more money into the import of energy carriers. The same applies to the GN-H_2-G scenario. Here, the energy carrier hydrogen is cheaper, but costs are incurred for the conversion of heating systems and the construction of hydrogen filling stations.

Figure 11: Comparison accumulated differential cost as per Scenario GN-Electricity



11 List of figures