The energy market in 2030 and 2050 – The contribution of gas and heat infrastructure to efficient carbon emission reductions

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SUMMARY

The present study investigates what contribution existing gas and heating networks can make to efficient greenhouse gas reduction by 2030 and 2050. To do this the study uses a total energy system model to quantify two possible scenarios for GHG reduction, in accordance with the German climate targets for 2030 and 2050. The Revolution scenario is based on a regulatory approach and enforced electrification of final energy consumption sectors, so that gas and heating networks become less and less important. Despite comprehensive electrification, this is not an "all-electric" scenario but is clearly moving in that direction. In the Evolution scenario, there is no regulatory requirement for any specific technologies, so that existing gas and heat networks can continue to be used, so long as it is economic to do so. The investigation focuses on the electricity and heating markets.

The main conclusions of the study are as follows:

1. The GHG reduction targets can be achieved in both scenarios – even in the non-technology-specific Evolution scenario.

The GHG reduction targets of 55% by 2030 and 95% by 2050 (relative to 1990 levels) are achieved in both the Evolution and the Revolution scenarios for the sectors analysed (energy industry, buildings and industry (excluding process emissions)). Breaking down GHG emissions by sectors, as in the Klimaschutzplan, is not cost-efficient.

2. The Evolution scenario is €139 billion cheaper than the Revolution scenario.

By 2030, the Evolution scenario will have saved €24 billion relative to the Revolution scenario (cumulated and undiscounted). A further €115 billion would be saved between 2030 and 2050. It is therefore cost-efficient to allow the market to decide what heating technologies to use to achieve efficient GHG reduction. If heat pumps were to become more advantageous in future, a market-led environment would allow them to gain a greater market share. Although, in the Evolution scenario, spending on fuel imports is approximately €252 billion higher, especially for synthetic fuels, this is offset by approximately €276 billion in savings on capital costs for power plants, heating appliances and insulation. Additionally, network costs for electricity, gas and heat networks are around €52 billion lower and save €95 billion of spending on imported electricity. Potential dismantling costs for gas and heat networks are not included in the cost calculation. If these were to be quantified, this would show further cost advantages in favour of the Evolution scenario. Investment costs in new industrial facilities have not been considered. If they were considered, the Evolution scenario would bring further cost advantages but these cannot be reliably quantified based on the data currently available.

3. The Evolution scenario offers more flexibility and opportunities for uncertain future developments.

The Evolution scenario is not only less expensive in the medium term up until 2030 but also keeps all options open in the longer term to respond to any currently unforeseeable developments after 2030, e.g. technological developments. If, for example, synthetic fuels were to become much cheaper, the Evolution scenario offers even greater economic advantages over the electricity-based energy system of the Revolution scenario. In the period up until 2050, the Evolution scenario is associated with a cost advantage of €192 billion. If, on the other hand, electricity-based technologies become cheaper, there is still the option within the Evolution scenario to switch over to a strategy of increased electrification – based on the assumptions made, this is still €129 billion cheaper than the Revolution scenario. No lock-in effects occur in the Evolution scenario before 2030, since technology decisions will still have to be made after 2030. Therefore no financial disadvantages or disadvantages in terms of achieving GHG targets are to be expected. An early commitment to a specific technology, as in the Revolution scenario, is then only economically advantageous if significant lock-in effects occur in the Evolution scenario – for example, if heat pumps become extremely cheap by 2030 or the assumed downward trend in costs for synthetic fuels are way off the mark. However, from the current perspective, these developments, which would be necessary to produce a lock-in, do not seem realistic. Consequently there is no need to make a premature commitment to enforced electrification.

4. In the Evolution scenario, gas-fired heating continues to be the dominant heating technology over the assessment period up until 2050; the Revolution scenario is dominated by the heat pump.

In the Evolution scenario, a large proportion of residential buildings are heated by – increasingly synthetic – gas. From the current approx. 9 million residential buildings, the penetration would increase to more than 11 million by 2030, followed by a slight drop to approx. 9 million by 2050. The number of heat pumps remains constant at the current level of 0.7 million up until 2030 and then increases to just about 6 million by 2050. In the Revolution scenario, there is a politically driven increase to more than 6 million heat pumps in 2030 and more than 13 million heat pumps in 2050, with corresponding repercussions on guaranteed capacity.

5. In the Revolution scenario, electricity demand increases by 70% compared to today in terms of the amount of electricity; and by 60% in terms of required capacity.

Greater electrification of the final energy consumption sectors increases electricity demand to 640 TWh in 2030, 120 TWh more than today. By 2050 it would increase by a further 250 TWh to nearly 900 TWh. Electricity demand increases in the Evolution scenario too, but only moderately to around 750 TWh. Most of this rise is down to the assumed changes in the transport sector. In the Revolution scenario, today's requirement for guaranteed capacity increases by approx. 89 GW to approx. 110 GW in 2030 and 142 GW in 2050. Although the capacity requirement also increases in the Evolution scenario, it is significantly lower at just 106 GW in 2050.

6. In both scenarios electricity generation from renewable energies doubles by 2030 and quadruples by 2050.

In both scenarios, the specified GHG reduction targets require the German electricity mix to have lower CO_2 emissions. Accordingly, electricity generation from renewables increases in both scenarios from the current level of approx. 180 TWh to approx. 420 TWh in 2030 and 760 or 790 TWh in 2050. Approximately two thirds of this come from wind farms and a good fifth from photovoltaics. The rest is generated from biomass and hydropower. The limits of the potential of onshore wind and solar plants in high-yield regions are reached in both scenarios. In order to integrate such large quantities of electricity from renewables into the network, digitisation and significant expansion of electricity distribution and transmission networks are essential.

7. In the Revolution scenario, the current capacity of gas-fired power stations will triple by 2050.

Due to the high level of electrification in the final energy consumption sectors in the Revolution scenario, the requirement for guaranteed capacity will also increase. Gas-fired power stations are the cheapest option for covering peak loads or two-week-long periods with no sun or wind. Accordingly, the installed capacity of gas-fired power stations will increase from the current 30 GW to 110 GW in 2050. Batteries can only help during short (e.g. less than a day) load peaks but not over a longer period of "Dunkelflaute[1]". Even in the Evolution scenario, the installed capacity of gas-fired power stations increases to 75 GW in 2050.

8. Synthetic fuels are an essential requirement in both scenarios in order to meet ambitious climate goals, and are largely imported.

Certain applications, particularly in industry and transport, can only be electrified at high cost and with a great deal of technical effort, if at all. Moreover, gas-fired – synthetic gas-fired in 2050 – power stations have to provide the guaranteed capacity, e.g. during periods with no sun or wind. Consequently, with 448 TWh (Revolution) and 634 TWh (Evolution), there is a significant requirement for synthetic fuels in 2050 in order to meet climate targets. In both scenarios, these quantities are so large that, given Germany's limited potential area for renewable electricity generation, substantial amounts of synthetic fuels would have to be imported from abroad.

9. There is a long-term requirement for gas transmission networks in both scenarios.

It is expected that there would be a large increase in gas-fired power plant capacity in both scenarios, in order to provide guaranteed capacity in the residual peak or in a period of dark doldrums. For simplicity, it is assumed that these power plants are directly supplied with gas by the gas transmission network. Even if the demand for gas – increasingly synthetic gas after 2030 – drops sharply, especially in the Revolution scenario, there is still a very high demand for capacity to supply the power plants with gas in situations of residual peak load for electricity. Thus, although the average utilisation of the transmission networks is relatively low, peak utilisation is

[1] The German term "Dunkelflaute" means a longer period (in this study two weeks) with little sunshine and wind and hence only little generation from renewables.

very high. The annual capacity utilisation is much higher in the Revolution scenario. Both of these facts illustrate that the gas transmission networks are essential for achieving GHG reduction targets in both scenarios.

10. In the Revolution scenario, existing gas distribution networks will lose value in the long term, whereas their value will be utilised to achieve climate targets in the Evolution scenario.

Due to the growth of heat pumps and electrical applications in the final energy consumption sectors in the Revolution scenario, utilisation of the gas networks will decline due to falling gas demand in the distribution network. If network charges remain the same, this will mean lower profits for network operators and hence lead to a devaluation of existing gas distribution assets. If network charges are increased to balance this out, gas will become increasingly economically unattractive for end customers, which might lead to a further drop in demand. This would result in even higher network charges and ultimately to a downward spiral. Since network operators can only offset falling demand to a certain extent by increasing network charges, this produces a problem in the refinancing of gas distribution infrastructure. Since gas demand drops sharply by 2050 in the Revolution scenario, distribution networks will also be partially dismantled, giving rise to additional costs. Moreover, in the case of a marked downward cost trend in the production of synthetic fuels in the Revolution scenario, the gas distribution networks would no longer be fully available, so that synthetic gas could not be used directly in end-use applications. In the Evolution scenario, the gas infrastructure can be utilised to a permanently high level up until 2050, so that there is no refinancing problem and the gas network retains its value.

11. Heat networks have denser coverage in the Evolution scenario, thus contributing to cheaper energy supplies for buildings.

In the Evolution scenario, there is a greater density of district and local heating networks, hence reducing the costs of district heating per kilowatt hour. In the Evolution scenario, 1.6 million buildings are supplied with 83 TWh of heat in 2050, which is approximately 10% more than the current volume. Furthermore, industry will also be supplied to some extent with grid-based heat. The number of buildings heated by district and local heating declines in the Revolution scenario. This means higher costs per kilowatt hour and hence the same financing problems for operators of heating networks as for gas distribution networks.

Conclusion: The results of the model calculations allow us to draw the following conclusions regarding the use of existing gas and heat infrastructure. The infrastructures...

- ... are needed to meet the climate targets cost-efficiently between now and 2030 looking towards 2050,
- … offer the option for efficient CO_2 reduction in a currently unforeseeable future after 2030,
- … do not exclude any other technology options, since lock-in effects are highly improbable before 2030,
- … will be devalued in the event of extensive electrification, especially at distribution network level,
- … offer a systemic advantage due to the storability and transportability of energy, since they will help to avoid expansion of the electricity network and any sharp rise in demand for guaranteed power plant capacity, and hence high retrofitting costs (heating, insulation) in the heating market.

1 INTRODUCTION

1.1 Background of the study

In its Klimaschutzplan 2050, the Federal Government of Germany defined targets for reducing GHG emissions. By the year 2050, GHG emissions should be 80% to 95% lower than in 1990. Moreover, a reduction of 55% compared to 1990 should already be achieved by 2030. The target for 2030 is further amended by sector-specific reduction targets for the Energy industry, Buildings, Transport, Industry and Agriculture, which in each case define the percentage contribution of the individual sectors to the overall reduction targets. Table 1 gives an overview of the individual targets within the Klimaschutzplan.

Sector	Emissions in million t CO_2 equivalent					% reduction relative to 1990	
	1990	2005	2014	2030	2050	2030	2050
Energy industry	466	397	358	183	no sector-specific provisions	61%	no sector-specific provisions
Buildings	209	154	119	72		66%	
Industry	283	31	181	143		49%	
Transport	163	160	160	98		40%	
Agriculture	88	160	72	61		31%	
Other	39	90	12	5		87%	
TOTAL	1248	992	902	562	62 to 250	55%	80% to 95%

TABLE 1: GHG REDUCTION TARGETS ACCORDING TO THE KLIMASCHUTZPLAN

Table 1 illustrates that achievement of the climate targets means wide-ranging changes in the relevant sectors. Whereas, over the last few years, the energy transition was primarily focused on the use of renewable energies within the electricity sector, this will require possibilities for avoiding emissions in all relevant sectors to be identified and implemented in the future. Sector coupling will play a central role in implementation. This term refers to the cross-sector optimisation of greenhouse gas reduction by the German economy through the exploitation of any synergistic effects that might exist between the individual sectors.

Two concepts that are being intensively discussed under the heading of sector coupling are the use of synthetic fuels, especially Power-to-Gas, and electricity-based heat production and engines in the Transport sector. Power-to-Gas refers to the electrolysis-based production of methane or hydrogen for use in Buildings, Industry and Transport. Alternatively, electricity can be used directly to generate heat or to power electric vehicles. A final assessment of these concepts in terms of cost-optimised greenhouse gas reduction in the energy sector and the consumer sectors is still pending.

A pathway to achieving climate targets that is frequently outlined in the current debate is electricity-driven greenhouse gas reduction of the consumer sectors Industry, Buildings and Transport (see e.g. BMWi 2017). This pathway is based on a rapid increase in the direct use of renewable electricity e.g. for electric vehicles, heat pumps or Power-to-Heat plants and a decline in other energy carriers such as gas, oil and district or local heating. At the same time, it is assumed that there will be ambitious improvements in energy efficiency. Due to the comparatively high level of efficiency of power applications, the use of zero-carbon electricity is the obvious solution for reducing CO_2 in the final consumer sectors, particularly if one focuses on supply and demand in relation to annual output. If one looks more closely at the geographic and temporal structure of energy supply and demand – i.e. fluctuating renewables and the huge seasonal and daily variations in demand (e.g. in the heat market) – predominant electrification requires new electricity networks and energy storage. At the same time, existing infrastructure such as gas or heat networks is not utilised to the same extent in such a scenario and could possibly lose value.

In order to make a comprehensive economic assessment of an efficient carbon reduction strategy, it is therefore necessary to examine the contribution made by the existing gas and heat infrastructure. Existing gas and heat infrastructure could contribute to the efficient achievement of carbon reduction targets, both in the short and medium term. With an increasing proportion of renewables, they might even become more important in the long term:

- Through the intermediate step of power-based production of synthetic energy carriers (methane or hydrogen via Power-to-Gas), the gas network could become a key technology for transporting and storing fluctuating renewables production.
- District and local heating networks could serve as heat storage to guarantee usage that is oriented towards the availability of renewable power, e.g. via Power-to-Heat plants that generate electricity-based heat for distribution via the heat network.
- Then there would be no need to expand power transmission and distribution networks. The need for electric storage devices could be reduced.
- Conventional power stations might be necessary as backup capacity, ideally using cogeneration (CHP).

A premature decision in favour of large-scale electrification of the final energy consumer sectors could prove to be economically disadvantageous in the medium and long term,

- since it reduces flexibility to react to uncertain future changes, such as possible technological advances,
- since the scalability of electrification is completely unknown and is potentially only achievable in combination with large-scale energy efficiency measures.
- since it creates a one-sided infrastructural dependency on electricity networks and reduces the current security of supply provided by the redundancy of different energy infrastructures.

The aim of this study is to examine the contribution of the existing gas and heat infrastructure to efficient CO_2 reduction in line with the climate targets. The analysis focuses on developments in the power and heat sector in the period up until 2050. The investigation is based on the comparison of two different scenarios (see Section 1.2), each achieving the climate targets for

2030, 2040 and 2050: the Revolution scenario assumes a great possible degree of electrification in the heat market and a gradual decline in the importance of gas and/or heat networks. The Evolution scenario makes no assumptions about possible electrification but allows for a solution that does not favour any particular technology. Existing gas and heat networks are used for as long as possible in the interests of economic efficiency. Both scenarios are quantified using the DIMENSION+ energy system model, modelling the associated repercussions on the German and European electricity market (see Section 1.3).

1.2 Study design

The study is centred around two scenarios, each depicting a different way of implementing GHG reductions in Germany up until 2050:

In the Revolution scenario, it is assumed that the electricity sector is the major driver for implementing the emission reduction targets. This scenario assumes politically accelerated electrification of the energy consumer sectors, leading to extensive electrification by 2050. Consequently, it is assumed that GHG reduction is achieved by electrification in all sectors, for example by the increased use of electricity-based technologies for heat generation in Buildings and Industry. Thus, for example, it is assumed that at least 6 million heat pumps will be installed in private households by 2030 and more than 13 million by 2050. This also implies an increased requirement for additional electricity infrastructure to integrate the new technologies. Thus the Revolution scenario represents a regulation-controlled continuation of the energy transition, focusing on the electricity sector.

In contrast, the Evolution scenario assumes integrated and non-technology-specific GHG reduction in power and heat production. Taking into account all available technology options, the existing infrastructure is used to produce the best possible overall results in terms of efficient greenhouse gas reduction, profitability and security of supply. Thus, in contrast to the Revolution scenario, no particular emphasis is placed on the electricity sector as the key element in reducing greenhouse gases.

In order to analyse the adaptability of both scenarios to central uncertainties, this study also examines how the two scenarios develop if electricity-based or gas-based technologies experience a greater technological push after 2030 than was originally envisaged.

The structure of the described scenarios is schematically represented in Figure 1. Based on the illustrated structure, the study is divided into three main sections:

- The first section (Chapter 2) outlines the Revolution scenario. The aim of this first section is therefore to provide a consistent illustration of cross-sector greenhouse gas reduction in the German economy with the emphasis on electricity-based technologies up until 2050.

- The second section (Chapter 3) outlines the Evolution scenario. This projects an alternative path to greenhouse gas reduction by 2050, wherein no specific technology is favoured. Of particular interest here is the comparison of the results with those of the Revolution scenario.
- The third section of the study (Chapter 4) examines whether it would be advantageous in the longer term to avoid focusing on a specific technology at an early stage (as assumed in the Evolution scenario), since this would leave open the possibility of reacting to uncertain future developments.

Based on the results of the study, Chapter 5 then assesses the value of the existing gas and heat infrastructure.

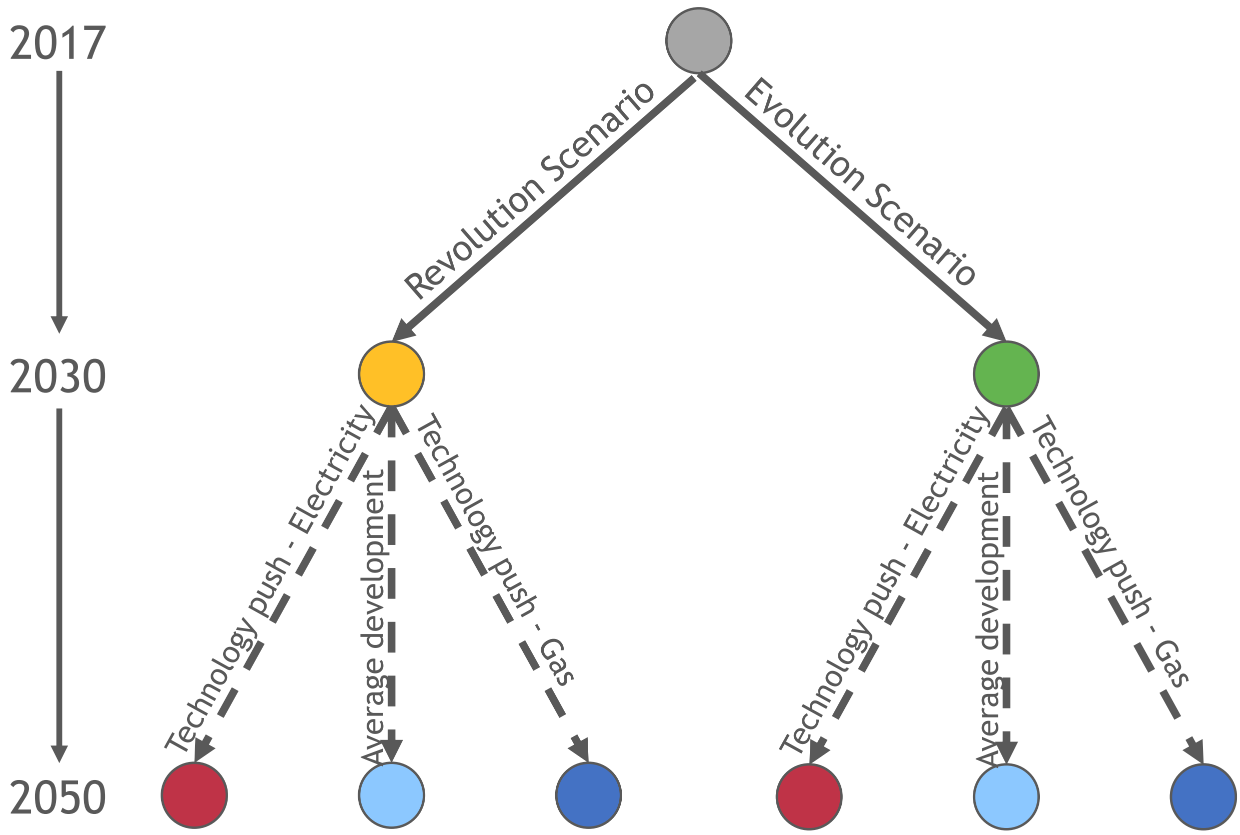

FIGURE 1: SCHEMATIC REPRESENTATION OF THE SCENARIOS

1.3 Methodology

The described scenarios are modelled using the DIMENSION+ energy system model developed by ewi ER&S, which includes the final energy consumer sectors: Buildings, Industry, Transport and Energy industry (i.e. the electricity sector including CHP). DIMENSION+ simulates the aggregated minimal-cost development of the stated sectors, taking account of the climate targets, and thus providing a consistent cross-sector model of scenarios for the future German energy supply system. Figure 2 shows the structure of DIMENSION+ used in this study.

On the demand side, the Building and Industry sectors are modelled endogenously, while the developments in the Transport sector are projected exogenously and are therefore identical in both scenarios. The final energy requirements covered by DIMENSION+ are obtained from the technological developments in the sectors. Primary energy carriers such as oil and natural gas or electricity generated in the power sector can be used for this. The electricity-based production of heat and fuels via Power-to-Heat, Power-to-Gas and Power-to-Fuel are explicitly depicted. From the produced quantities of energy energy prices are derived, which in turn influence energy demand. These interdependencies are endogenously identified, i.e. electricity and heat sectors are computed as an integral unit.

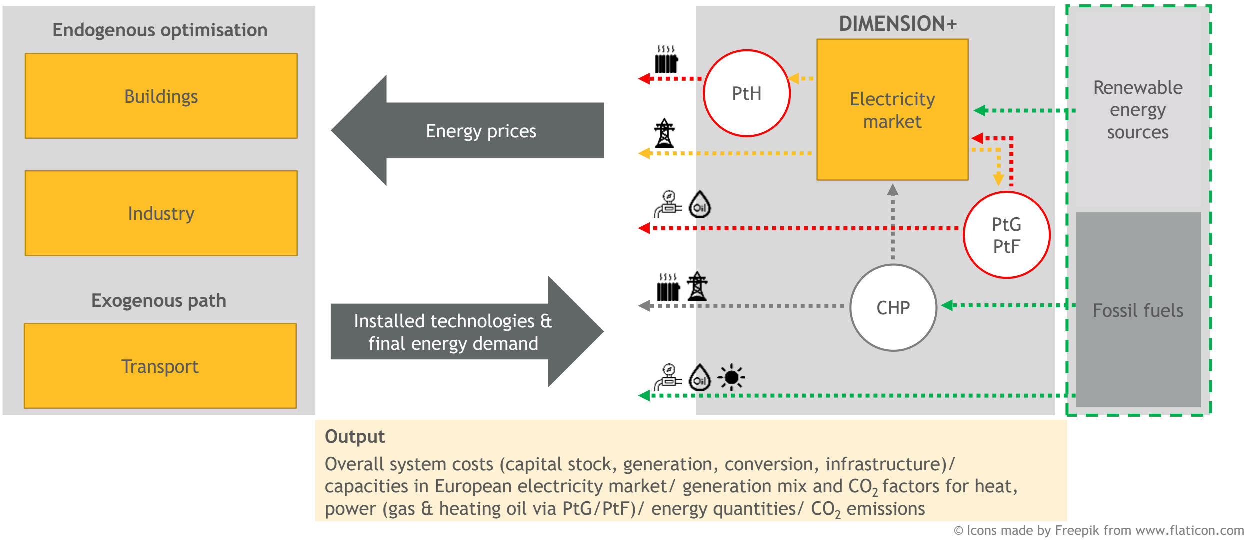

FIGURE 2: STRUCTURE OF THE MODEL DIMENSION+

Apart from the sectoral final energy demand, central input figures for the model are system costs, power generation quantities and capacities, installed heating technologies and CO_2 emissions. Key input parameters are prices for primary energy sources, investment costs and political framework conditions. Here the modelling of political requirements for CO_2 emissions are of crucial importance.

The relevant assumptions made for CO_2 targets are illustrated in Figure 3. The figure takes account of the endogenously modelled sectors: Energy industry, Buildings and Industry. Emissions in the Transport sector are derived from the exogenous development path. Hence, transport-related emissions are included in the targets and energy requirements but are not determined endogenously from the model. It should be noted that, in the Industry sector, only energy-related emissions are considered in the context of optimisation. Although process-related emissions (PE), such as from the production of steel or cement, are consistent with energy consumption and derived from the economic development in the industrial sector. They are not included in the modelled CO_2 targets, in order to keep the focus of the analysis on the energy sector. Emissions from agriculture and miscellaneous emissions are not explicitly considered. However, it is assumed that these sectors participate in the reduction of carbon emissions in keeping with cross-sector targets.

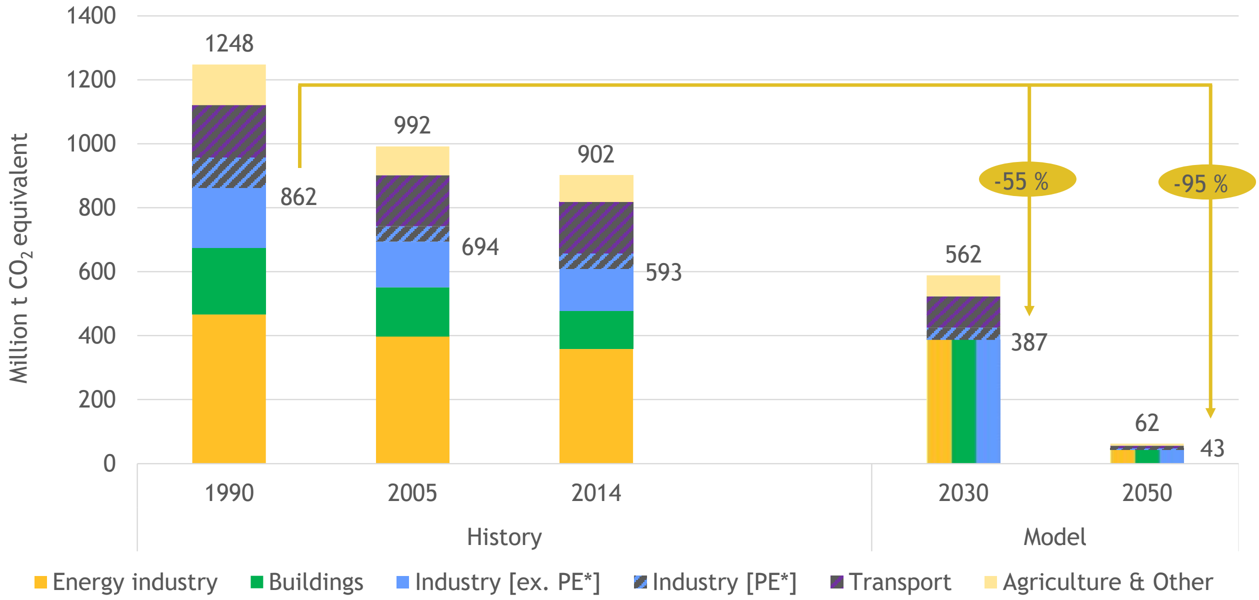

FIGURE 3: MODELLING OF CO_2 EMISSIONS

It is assumed that a cross-sector CO_2 reduction of 55% relative to 1990 is achieved by 2030. The sector-specific targets of the Klimaschutzplan are not considered, since these are not consistent with efficient cross-sector CO_2 reduction. A 95% cross-sector reduction of emissions in 2050 relative to 1990 is simulated in the Energy industry, Buildings and Industry sectors (excluding process emissions). This therefore gives a minimal-cost distribution of residual emissions between the Energy industry, Buildings and energy-related industrial emissions. Emissions from the Transport sector and process emissions from Industry in 2050 are derived from the exogenous development pathways. In order to achieve the national GHG reduction target of 55% and 95% respectively, the other sectors of Agriculture and Miscellaneous must also reduce their emissions by 55% and 95% respectively. Should this not be possible or successful in these sectors, the GHG reduction target would be missed or else the Building, Industry and Energy industry sectors would have to make additional reductions.

Finally, it should be noted that the chosen specification with cross-sector targets allows GHG emissions to be reduced in Germany at minimal cost over the considered sectors. However, for sectors that are already regulated by the EU-ETS, national targets related to a global reduction in GHG emissions are not economically efficient. This applies to the German national climate target, which is overlayed on the EU-ETS for the electricity sector (and parts of industry). Since the national target must be achieved within the same timeframe as the EU-ETS, there is a risk of misallocation of CO_2 emissions i.e. the reduction in the German electricity and industrial sector could allow countries to use the freed EU-ETS certificates, so long as Germany does not disable them. This effect can also mean that German electricity imports have a higher CO_2 content than domestic power production.

A detailed description of the model used and the methodology can be found in the Appendix.

2 REVOLUTION SCENARIO

2.1 Definition of the scenario

The Revolution scenario models greenhouse gas reduction in the German energy system driven by the electricity sector. Accelerated electrification is assumed in all considered sectors and this is combined with an increase in energy efficiency and intensified expansion of renewable energies in the electricity sector. The central assumptions of the Revolution scenario are outlined below. In addition to this, there are various parameters that are assumed to be the same in all scenarios in this study. These are outlined in the Appendix.

The central assumption in the Building sector is a focus on electricity-based heating technologies, in particular heat pumps. It is assumed that there will be 6 million heat pumps installed by 2030. This value is based on the target value stipulated in Agora Energiewende 2017. It is assumed that there is a linear increase in installed heat pumps between 2017 and 2030. The target value is then increased to 13 million heat pumps in 2050. These assumptions equate to a minimum expansion of nearly 350,000 heat pumps per annum. It is further assumed that there is wide-ranging renovation of the building stock. Based on the Agora Energiewende 2017 results, a renovation rate of 2% per annum is assumed. Compared with the current renovation rate of approx. 0.8% per annum, this therefore represents a much greater reduction in final energy demand in the heat sector. Due to the high renovation rate and the strong reliance on decentralized heat pumps, it is further assumed that the potential for centralised district and local heating will fall from the current level of 47 TWh to approximately 25 TWh in 2050.

	2015	2030	2050
< 100 °C	12%	35%	90%
100-500 °C	9%	25%	60%
500-1.000 °C	9%	15%	30%
> 1.000 °C	7%	10%	20%

TABLE 2: PERCENTAGE OF ELECTRICITY-BASED PROCESS HEAT PRODUCTION IN INDUSTRY BY TEMPERATURE LEVEL

It is further assumed that there is greater use of electricity-based technologies to provide process heat in the Industry sector. The available potential for electrification in Industry is a function of the particular branch and required temperature level, since different technical options exist for producing heat in each instance. Consequently, pathways for the penetration of electricity-based technologies that are differentiated according to temperature level are assumed. Table 2 shows the assumed percentages of electricity-based process heat production, differentiated according to required temperature levels.

Exogenous development is assumed in the Transport sector (only road transport in this case), which presumes accelerated electrification of the vehicle fleet. An increase in the percentage of electric vehicles to 70% in 2050 is assumed for both private cars and light duty vehicles. The percentage is assumed to be 30% in 2030. With a slight increase in mileage, this corresponds to 33 million electric cars and 2 million electric light duty vehicles. Thus the electricity demand in the Transport sector increases to 28 TWh in 2030 and 69 TWh in 2050. Figure 4 shows the resulting final energy demand and CO_2 emissions for the Transport sector.

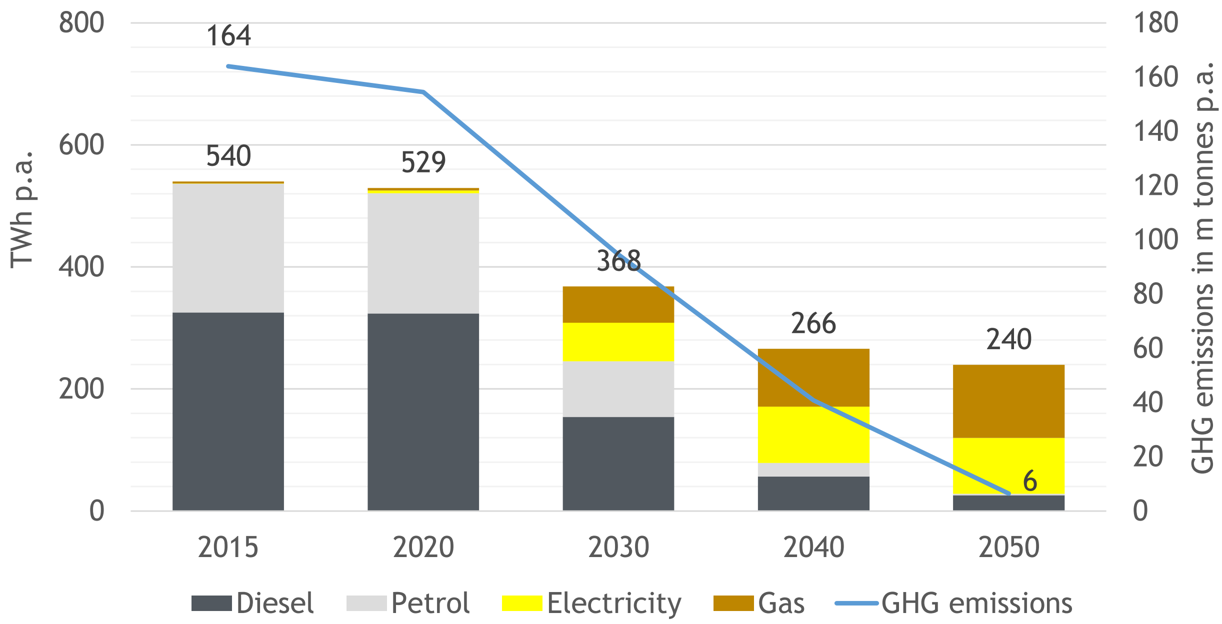

FIGURE 4: FINAL ENERGY CONSUMPTION AND CO_2 EMISSIONS FOR THE ROAD TRANSPORT SECTOR

2.2 Development of GHG emissions

In keeping with the targets, by 2030 GHG emissions for the Energy industry, Buildings and Industry sectors will fall by 55% relative to 1990 to 378 million t CO_2 equivalent and by 95% relative to 1990 to 43 million t CO_2 equivalent by 2050. Compared with 2015, this corresponds to an additional reduction of 37% by 2030 and 93% by 2050. The described reduction pathway is schematically represented in Figure 5.[2]

[2] The illustration does not include any process emissions.

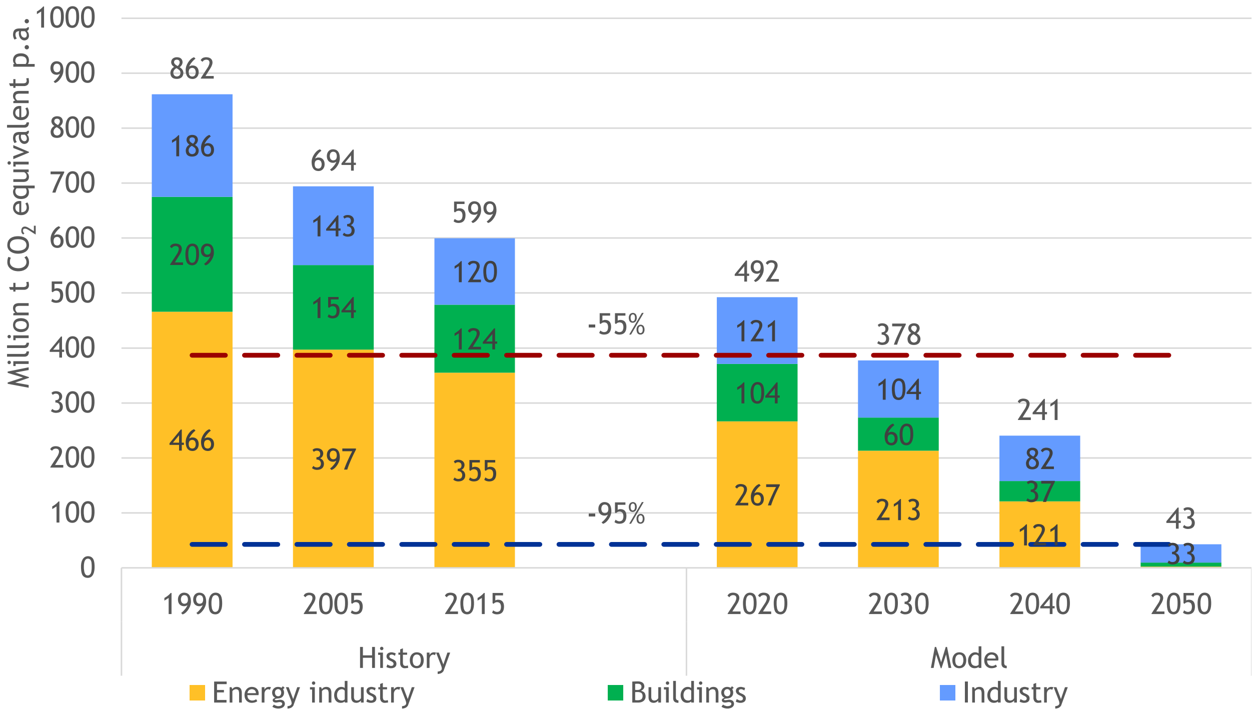

FIGURE 5: DEVELOPMENT OF GHG EMISSIONS IN THE REVOLUTION SCENARIO

Figure 5 illustrates that implementation of the 95% target by 2050 is associated with almost complete carbon neutrality of the German energy sector. However, at the same time, the electricity that is imported still has a low CO_2 intensity, in keeping with the EU-ETS. At a level of 33 million t CO_2 equivalent, by far the largest percentage of residual emissions is claimed by the industrial sector. The Buildings and Transport sectors are still responsible for 7 million t CO_2 equivalent and 6 million t CO_2 equivalent respectively in 2050. The technological and structural changes that lead to the illustrated development in the individual sectors are outlined in the following sections.

2.3 Final energy demand

2.3.1 Building sector

2017 TO 2030

For reducing greenhouse gases in the Building sector[3], the Revolution scenario assumes extensive expansion of heat pumps in residential buildings. By 2030 heat pumps are the primary source of heat in more than 6 million buildings. These primarily replace oil-fired heating systems in the technology mix and, to a lesser extent, gas-fired heating systems. The most advantageous solution

[3] For the purposes of this study, the Building sector includes final energy demand for space heating and hot water in private households, commerce and industry. It also includes the energy demand of residential users for air conditioning, lighting, mechanical energy, ICT, process cooling & miscellaneous process cooling and other process heat. This breakdown of areas from the AG Energiebilanzen (Energy Balances Working Group) corresponds to that of the Klimaschutzplan.

is the installation of heat pumps, particularly in well insulated detached houses or new builds. Figure 6 shows the number of primary heating systems in residential buildings.

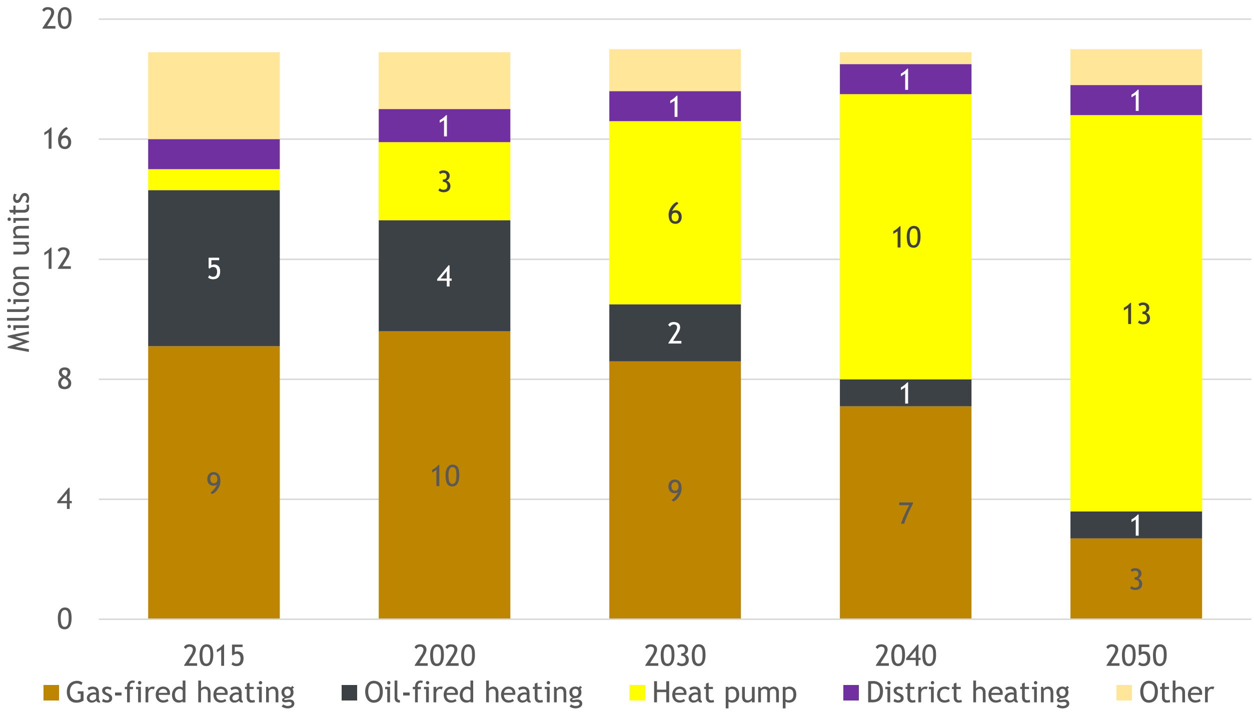

FIGURE 6: PRIMARY HEATING SYSTEMS IN RESIDENTIAL BUILDINGS IN THE REVOLUTION SCENARIO

Due to the technological requirements of heat pumps and the necessary improvements in energy efficiency, building insulation measures are of crucial importance in the Revolution scenario. By 2030, total final energy demand in the Building sector is reduced by 28% relative to the actual level in 2015. Figure 7 shows the final energy demand for space heating and hot water resulting from the technology mix and insulation. Electricity demand increases to 60 TWh by 2030. Gas demand falls to 256 TWh by 2030.

2030 TO 2050

As can be seen from Figure 6, from 2030 onwards heat pumps increasingly replace gas heating and district and local heat, to allow the assumed expansion of heat pumps to 13 million units to be achieved by 2050. Heat pumps will also be increasingly used in older and larger residential properties. The number of installed gas-fired heating systems will fall by approx. 6 million between 2030 and 2050 to just 3 million heating systems. Note that oil-fired heating systems will still be represented in the technology mix in 2050, since not all houses have gas connections and not all residential buildings are sufficiently well insulated to allow the use of heat pumps.

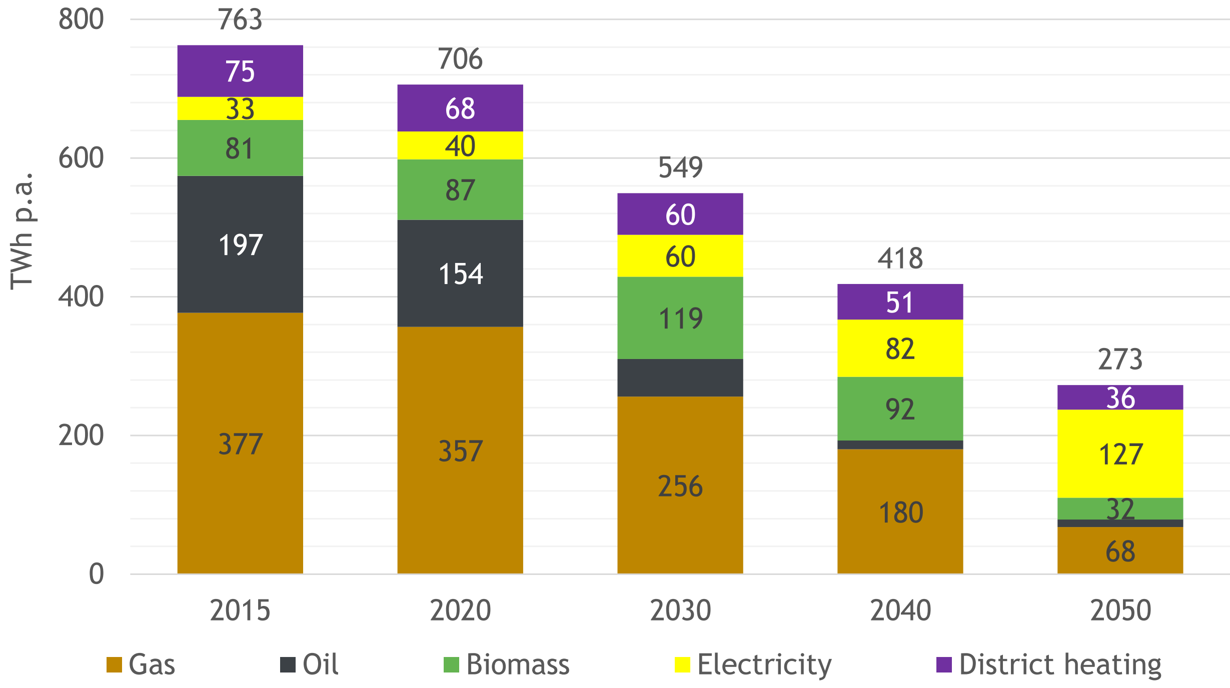

FIGURE 7: FINAL ENERGY DEMAND FOR SPACE HEATING AND HOT WATER IN RESIDENTIAL BUILDINGS IN THE REVOLUTION SCENARIO

As a result of improved insulation, overall energy demand (Figure 7) for space heating and hot water in the Building sector will drop by 2050, by 64% relative to 2015 and by 50% relative to 2030. Electricity demand will increase to 127 TWh by 2050. Due to the extra heat pumps, the percentage of electricity in final energy consumption will increase from 11% in 2030 to 47% in 2050. Hence, in the year 2050, electricity is by far the most important energy source for producing heat in residential buildings. Gas demand will drop sharply to 68 TWh in 2050.

2.3.2 Industry sector

The progression of the Industry sector is characterised by two opposed developments. On the one hand, it is assumed that there is an annual increase of 1.3% in gross value added and, on the other, a significant improvement in energy efficiency. This results in a significant increase in energy productivity and a more or less constant progression of total industrial energy demand. Because of the existing production processes and plants, the structure of industrial energy consumption is comparatively rigid, since, in some cases, switching over to power-based technologies would involve considerable modifications to the process chains or even the construction of completely new production facilities. As a result, the suitability of electricity as an energy source for producing process heat varies from branch to branch. It is primarily the branches that require a comparatively low temperature level for production process heat that are suitable for electrification of their processes. For example, these include the paper industry, food industry and some parts of the chemical industry.

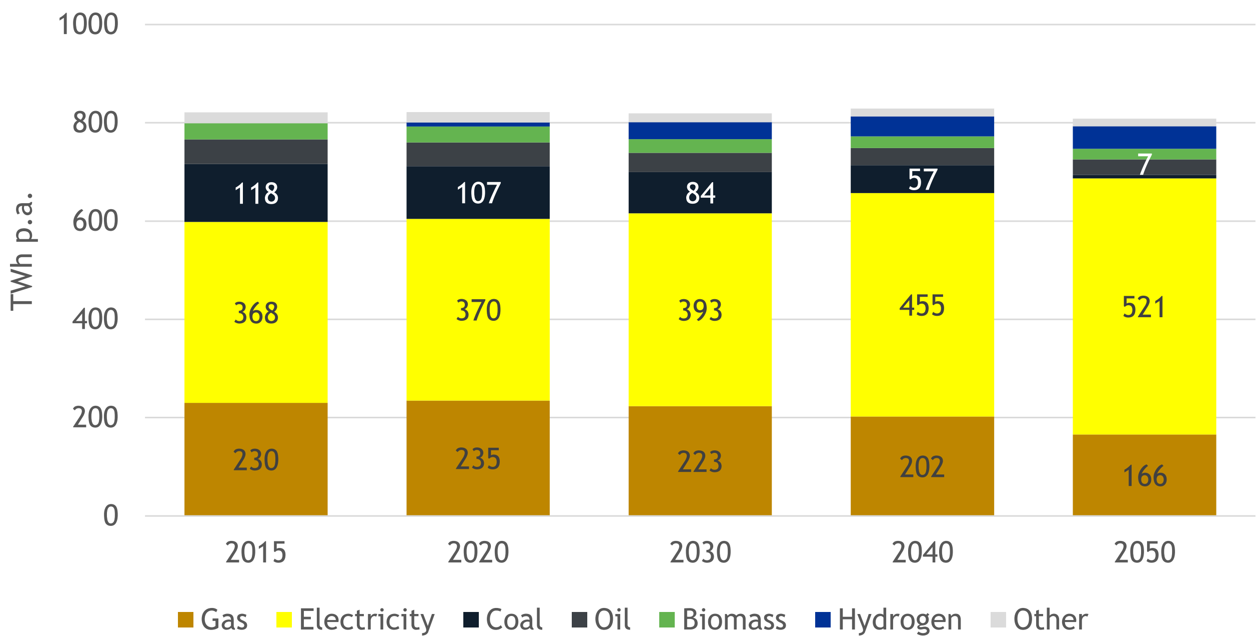

FIGURE 8: FINAL ENERGY DEMAND IN INDUSTRY IN THE REVOLUTION SCENARIO

2017 TO 2030

Due to the above-mentioned rigid structure of industrial energy demand, there is a moderate increase in electricity consumption in Industry up until 2030, namely from 386 TWh in 2015 to 393 TWh in 2030. Gas demand falls slightly relative to 2015, from 230 to 223 TWh. The demand for coal also falls slightly from 118 TWh in 2015 to 84 TWh in 2030. In view of the relatively rigid production structures outlined above, the overall changes in industrial energy demand up until 2030 are relatively small. The development of the resultant final energy demand in the Industry sector is schematically represented in Figure 8.

2030 TO 2050

By 2050 there is further electrification of industrial processes, leading to a corresponding increase in electricity demand. It will increase from 393 TWh in 2030 to 521 TWh in 2050. Gas demand will decline between 2030 and 2050. Nevertheless, in 2050, gas is still the main energy source in the industrial energy mix, with a demand of 166 TWh. Even coal will continue to be an energy source in the 2050 energy mix, since the substitution of coal as a reducing agent in the steel industry could only be achieved by changing the entire production chain.

2.4 Electricity sector

The development of electricity demand in the Building, Industry and Transport sectors outlined in the previous sections changes the demands made of the electricity sector. The corresponding development of electricity production, power station capacity and external electricity trading is outlined below.

2.4.1 Net electricity production and net electricity demand

2017 TO 2030

Net electricity demand will increase to 701 TWh by 2030. This corresponds to an increase of 125 TWh or 22% relative to 2015. This increase is primarily due to the increasing demand for electricity in the Transport sector. This will increase from the current level of 12 TWh to 77 TWh. However, electricity demand will also increase in the other sectors considered. Due to the increased use of heat pumps, electricity demand in the Building sector will increase from 140 TWh to 161 TWh. Due to the electrification of production plants, industrial electricity demand will increase from 368 TWh to 393 TWh. On top of this, with a requirement of 11 TWh in 2030, significant amounts of electrical energy are used for the first time for electrolysis-based production of synthetic fuels.

The structure of electricity generation changes fundamentally over the period. The percentage of renewable energy sources in the generation mix will increase to 61% by 2030. The greatest increase is seen in electricity production from onshore wind energy, which will increase from 58 TWh in 2015 to 211 TWh in 2030. From as early as 2025, onshore wind energy will become one of the most important energy sources in the German electricity generation mix. Significant increases will also be seen in offshore wind energy and photovoltaics. Electricity production from offshore wind turbines will increase to 54 TWh in 2030. Electricity production from solar installations will increase to 85 TWh in 2030. From 2025 onwards, more than half of the German electricity is generated from renewable sources.

Conventional electricity production fall significantly over the period (cf. Figure 9). First of all, electricity production from nuclear plants will drop to zero, due to the political decision to phase out nuclear energy. Because of this decline, fossil fuels such as coal, hard coal and gas will still play a significant part in electricity production in 2025. By 2030 there will then be a significant reduction in the proportion of coal-fired power stations in particular. Nevertheless, even in 2030, 54 TWh will be generated from hard coal and 65 TWh from lignite. Total net electricity production initially only increases slightly to 654 TWh by 2030.

2030 TO 2050

The outlined development continues after 2030 or even accelerates. Net electricity demand increases to 959 TWh by 2050. This corresponds to a further increase of 257 TWh or 37% relative to 2030. This corresponds to a 66% increase relative to 2015. The percentage of renewable energy sources in net electricity production will further increase to 83% by 2050. This corresponds to a further increase in electricity generation from onshore wind energy to 373 TWh in 2050. Electricity generation from offshore wind energy and PV will also increase significantly between 2030 and 2050 to 139 TWh and 192 TWh respectively.

The decline in conventional electricity generation will also continue between 2030 and 2050. After 2030, coal-fired electricity generation will gradually disappear from the electricity production mix, so that by 2050 only gas-fired conventional power stations will remain, with a production of 84 TWh. The gas used for electricity production in 2050 will consist exclusively of synthetic fuels. Overall, net electricity production will increase sharply between 2030 and 2050 to 875 TWh. This equates to a relative increase of 36% compared with 2030. Figure 9 shows a graphic illustration of the development of net electricity production in Germany.

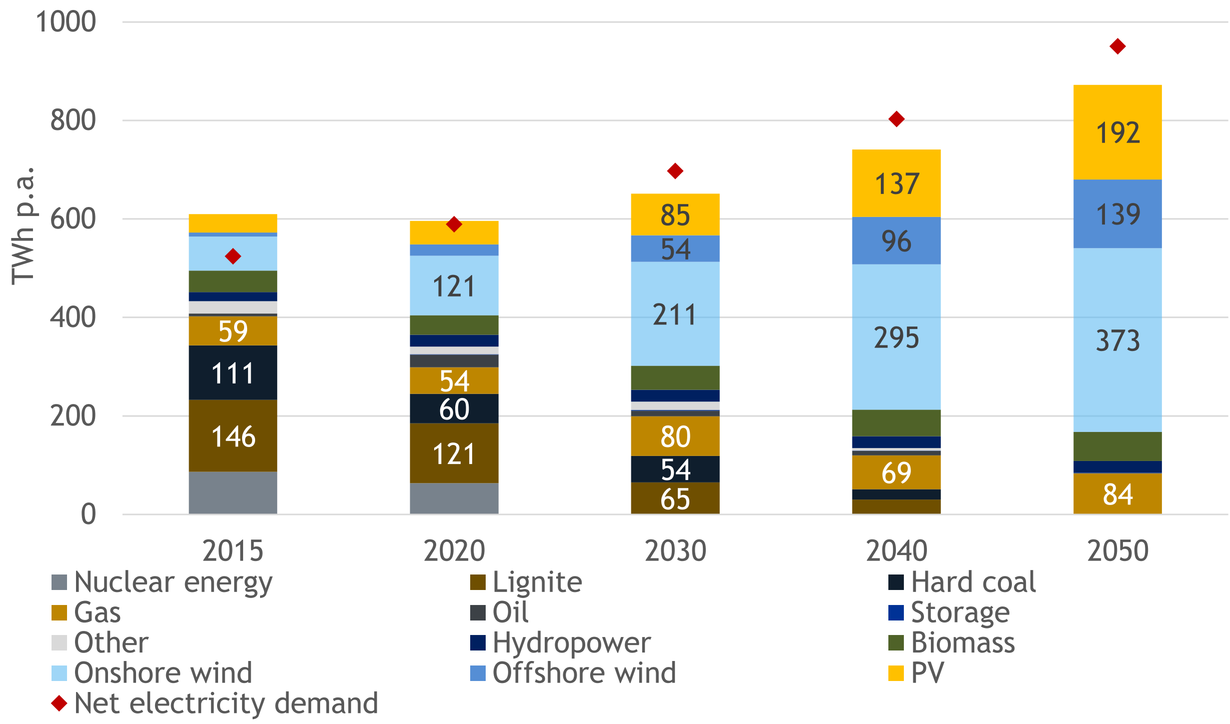

FIGURE 9: NET ELECTRICITY PRODUCTION IN THE REVOLUTION SCENARIO

2.4.2 Power stations

2017 TO 2030

In order to provide the described electricity production, the installed capacity of renewable-energy-based generation technologies will increase sharply up until 2030. The installed capacity of onshore wind turbines will more than double between 2015 and 2030 to 101 GW. The installed capacity of solar installations will show a similarly sharp increase from 38 GW in 2015 to 89 GW in 2030. Offshore wind turbines will be expanded to an installed capacity of 15 GW in 2030. This means that 4 GW net of new wind capacity and 3.4 GW of PV capacity will be added every year up until 2030. The development of renewable-energy-based power stations is schematically represented in Figure 10. The model only maps potential areas available for renewable energies but no network restrictions or acceptance issues e.g. relating to the expansion of onshore wind farms. It is therefore also possible that there might be more offshore wind farms and fewer onshore wind farms but this would not change the basic statement of the results.

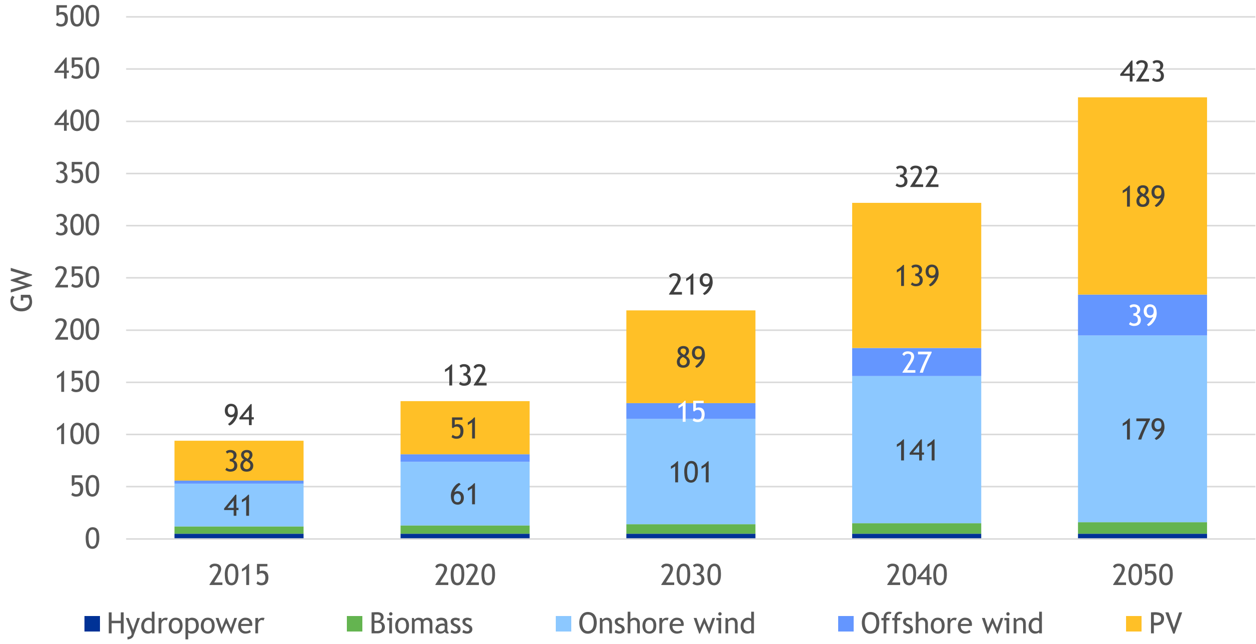

FIGURE 10: INSTALLED CAPACITY OF RENEWABLE ENERGIES IN THE REVOLUTION SCENARIO

In terms of conventional stations, nuclear energy is phased out by 2022. This is then followed by a gradual changeover to flexible gas-fired power stations, which, due to their comparatively low specific investment costs, could provide back-up capacity for weather-dependent and volatile feed-in from renewable energy sources. By 2030 the guaranteed installed capacity of gas-fired power stations (incl. gas-fired CHP) increases to 79 GW, which equates to an increase of 48 GW relative to 2015. The installed capacity of coal-fired power stations drops to 18 GW by 2030. Figure 11 shows the development of conventional power stations over time.[4]

The necessary guaranteed capacity in the electricity supply system will increase greatly in the Revolution scenario, due to intensive electrification and the correspondingly modified structure of electricity demand. There is a peak load of 93 GW by 2020 and this will increase significantly to 110 GW by 2030. Figure 12 shows the breakdown of peak load over the different sectors. It is clear that the increase up to 2030 is substantially due to increased utilisation of heat pumps in the Building sector. The peak load in the Transport sector will also increase to 14 GW by 2030, due to the more widespread use of electric vehicles. When interpreting Figure 12, it should be noted that the sum of the individual peak loads for the different sectors is greater than the

[4] Apart from covering an absolute peak load situation, the model must also be able to bridge a two-week period with minimal wind or sun. Over such a long period, storage such as e.g. batteries can only provide a limited contribution to covering demand. Hence only limited investment is made in batteries to cover peak load, particularly in the period up until 2030.

aggregated peak load in Germany. This is due to the different load profiles in each sector, which balance each other out, thereby leading to a reduction in aggregated peak load.

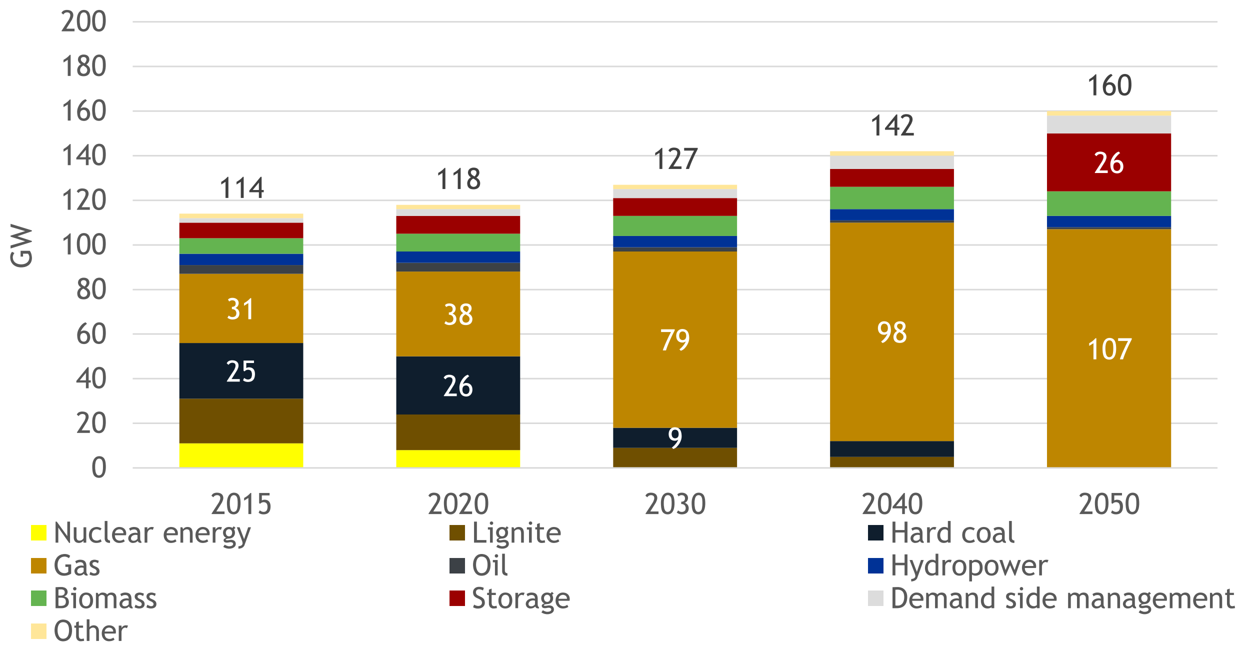

FIGURE 11: DEVELOPMENT OF CONVENTIONAL POWER STATIONS IN THE REVOLUTION SCENARIO

2030 TO 2050

The installed capacity of power stations based on renewables will continue to increase sharply between 2030 and 2050. The capacity of onshore wind farms increases to 179 GW by 2050, which equates to a quadrupling of the 2015 value and an increase of nearly 80 GW relative to 2030. Photovoltaics is expanded to a capacity of 189 GW by 2050. This corresponds to five times the installed capacity in 2015 and more than double the capacity in 2030. Offshore wind energy will likewise be greatly expanded between 2030 and 2050 to a value of 39 GW. The big expansion of onshore wind energy will lead to exhaustion of the assumed potential for onshore wind farms in 2050. The limits of potential areas for solar installations in the sunnier parts of Germany will also be reached.[5] By 2050, there will only be roof space left for solar installations in northern Germany.

Due to increasing electricity demand and the consequently increasing demand for guaranteed capacity, there is a significant increase in the installed capacity of conventional power stations between 2030 and 2050, to a total of 134 GW in 2050. Coal-fired power stations will remain as part of the power station fleet up until 2040, whereas in 2050 the conventional power station fleet is based almost exclusively on gas-fired power stations. These are expanded to a total capacity of 107 GW by 2050, equating to an increase of approximately 30 GW between 2030 and 2050. These also include gas-fired CHP, which will also be built to replace existing coal-fired CHP, for example.

[5] It is assumed that there is 10,000 km² of potential area for onshore wind in Germany, corresponding to 179 GW of installed capacity. Potential capacity of 105 GW (roof) and 158 GW (base) is assumed for PV. These areas are subdivided into different regions according to full-load hours inter alia.

Peak load will also continue to increase up until 2050, due to continued electrification, and is 142 GW in 2050. One of the main reasons for this increase is further expansion in the use of heat pumps, which will lead to a significant increase in peak load in the Building sector. Moreover, there is an increase in demand for guaranteed capacity in Industry, since production processes will increasingly be converted to use electricity-based technologies. The Transport sector will also have a significant requirement for guaranteed capacity in 2050. However, at 22 GW, this remains comparatively small compared with the Buildings and Industry sectors.

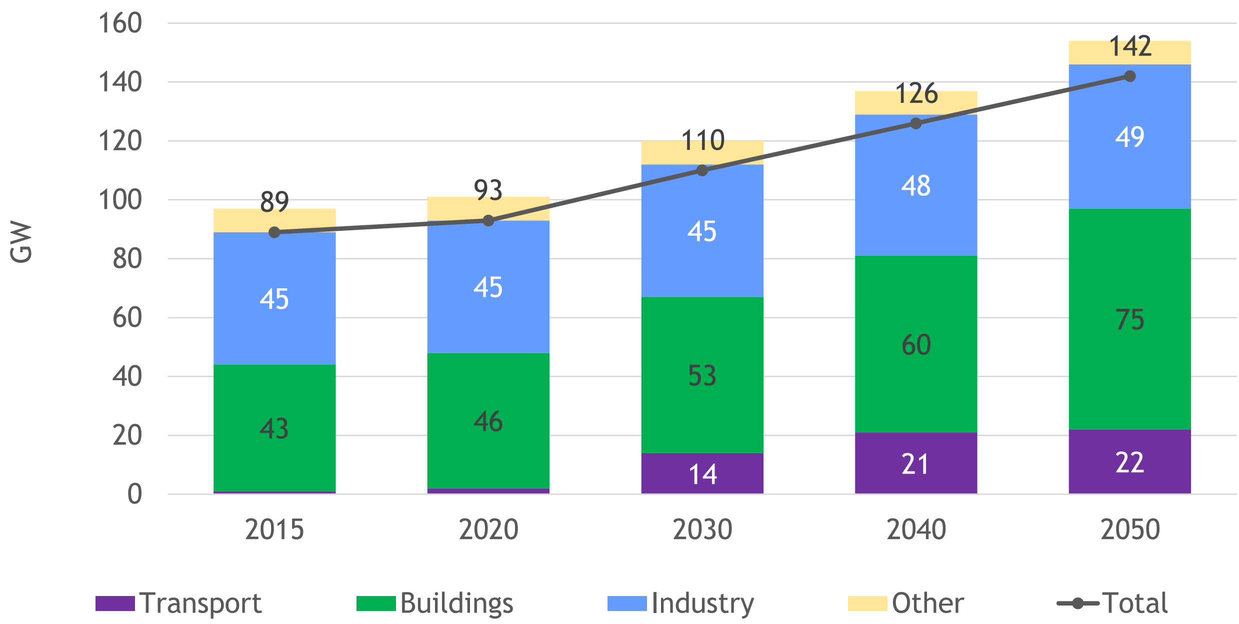

FIGURE 12: DEVELOPMENT OF PEAK LOAD IN THE REVOLUTION SCENARIO

2.4.3 External electricity trading

2017 TO 2030

Increasing domestic electricity demand will not only mean changes in the electricity generation mix but also changes in Germany's external electricity trading balance. By 2020, net electricity exports will drop to 9 TWh. Germany will become a net importer of electricity from 2030 onwards. Net electricity imports in 2030 are 43 TWh. This development is driven by the phase-out of nuclear energy in Germany and the rise in power demand due to increasing electrification.

The analysis of the rest of the European electricity market in Figure 14 shows that, in both scenarios, power production from renewables increases sharply in Europe up until 2030, to almost double the current values. Despite a slight increase in electricity demand, generation from hard coal (-44% compared with 2015), gas (-53%) and oil (-47%) declines sharply during the period up until 2030.

2030 TO 2050

Net electricity imports continue to increase between 2030 and 2050. In 2050, net German electricity imports are 76 TWh. The further rise in imports is due to Germany's ambitious CO_2 reduction targets. Because of these targets, electricity will increasingly be imported from abroad, in order to avoid domestic production from conventional energy sources. Because of the EU-ETS certificates that will still be around in 2050, it is assumed that electricity imported from abroad will still contain minimal amounts of CO_2. Figure 13 illustrates the temporal curve of exports, imports and net imports.

By 2050, generation from renewables will increase in Europe by a further 45% relative to 2030. Conversely, generation from coal and oil is reduced by more than 95% compared with 2015. This is attributable to the emission reduction targets, which will also become stricter throughout Europe. Generation from gas will only fall by 15% compared with 2015.

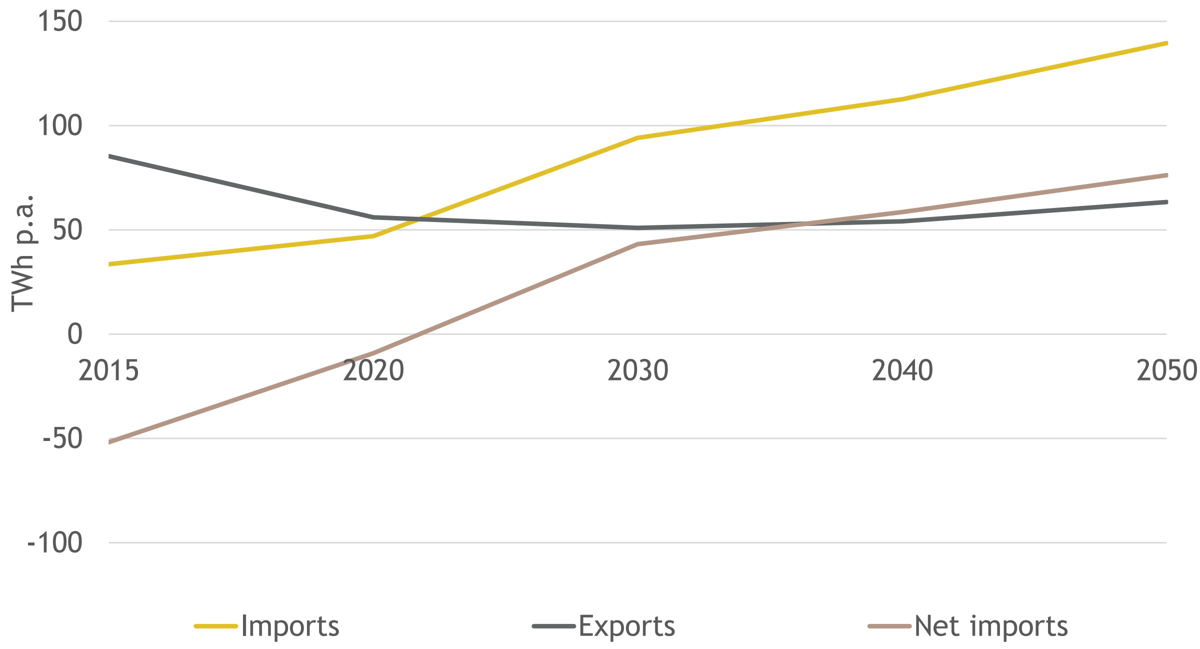

FIGURE 13: DEVELOPMENT OF GERMANY'S EXTERNAL ELECTRICITY TRADING IN THE REVOLUTION SCENARIO

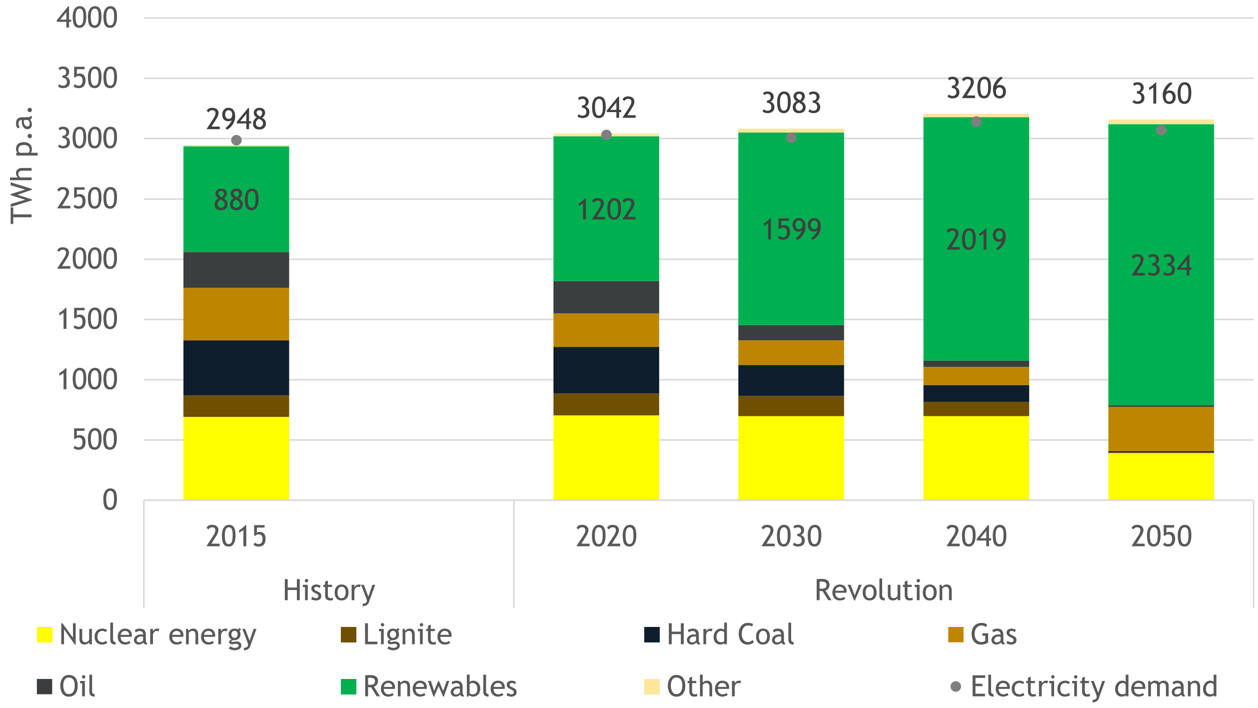

FIGURE 14: DEVELOPMENT OF EUROPEAN POWER PRODUCTION (EXCLUDING GERMANY) IN THE REVOLUTION SCENARIO[6]

2.5 Use of synthetic fuels

2017 TO 2030

Apart from the direct use of emission-free energy sources, synthetic fuels produced with emission-free electricity, can also be used to reduce GHG in energy supply. In the Revolution scenario, significant use is made of synthetic fuels from 2030 onwards, namely 30 TWh in the Transport sector and 10 TWh in the Industry sector. A major part of this requirement for synthetic fuels is imported from the rest of Europe.

2030 TO 2050

The demand for synthetic fuels in the Transport sector will increase to 87 TWh by 2040, while demand in the other sectors will remain unchanged. In 2050, the comprehensive use of synthetic fuels is then necessary in order to achieve the 95% reduction target in all sectors under consideration. For the first time, 147 TWh of synthetic fuels is then reconverted in the Electricity sector, in order to generate carbon-neutral electricity in times of low feed-in from wind and solar generation. In 2050, 29 TWh of synthetic fuels are also used in the Building sector. Consequently, despite an increase in the number of installed heat pumps to 13 million units, it is cost-efficient to use synthetic fuels for heat production in 2050. A further 95 TWh of synthetic fuels are required in the Industry sector, in order to implement the cross-sector 95% target. Finally, in 2050, the consumption of synthetic fuels will also increase sharply in the Transport sector to a figure of 177

[6] EU 28 excluding Malta and Cyprus, as well as Norway and Switzerland.

TWh. Overall, despite the emphasis on the electricity sector and the assumed high level of electrification in the Revolution scenario, there is considerable demand for synthetic fuels, in order to be able to achieve the 95% target. Apart from the intensive use in the Transport sector, the main drivers for this are that it is expensive to electrify some production processes in the Industry sector and also that the limited potential area in Germany (cf. 2.4.2) for electricity generation through wind and solar prevents more widespread use of renewables. The total demand for synthetic fuels in Germany in 2050 is 448 TWh. Figure 15 represents the results graphically.

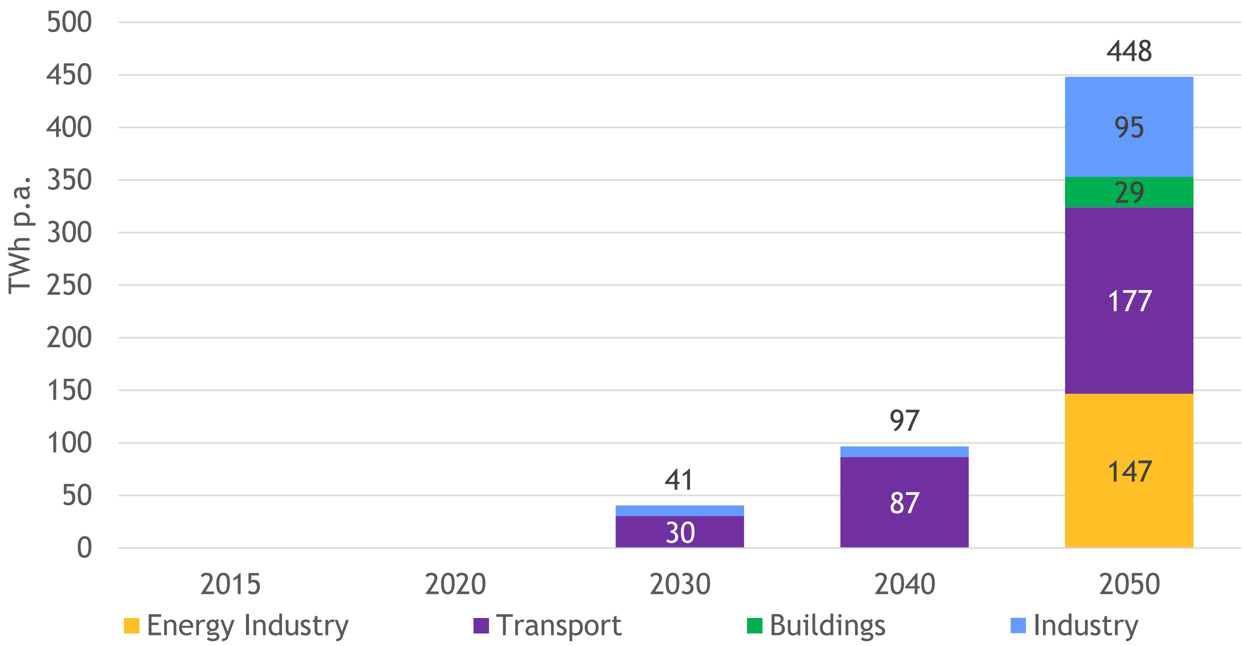

FIGURE 15: USE OF SYNTHETIC FUELS BY SECTOR IN THE REVOLUTION SCENARIO

Figure 16 additionally shows the breakdown of demand into the different types of synthetic fuels. It can be seen that the largest proportion is synthetic gas, i.e. methane, obtained via Power-to-Gas technologies. Moreover, the use of synthetic hydrogen, which is primarily used in the industrial sector, also increases over time. Considerable quantities of synthetic fuels are also consumed in 2050. The total demand for synthetic gas in 2050 is 267 TWh.

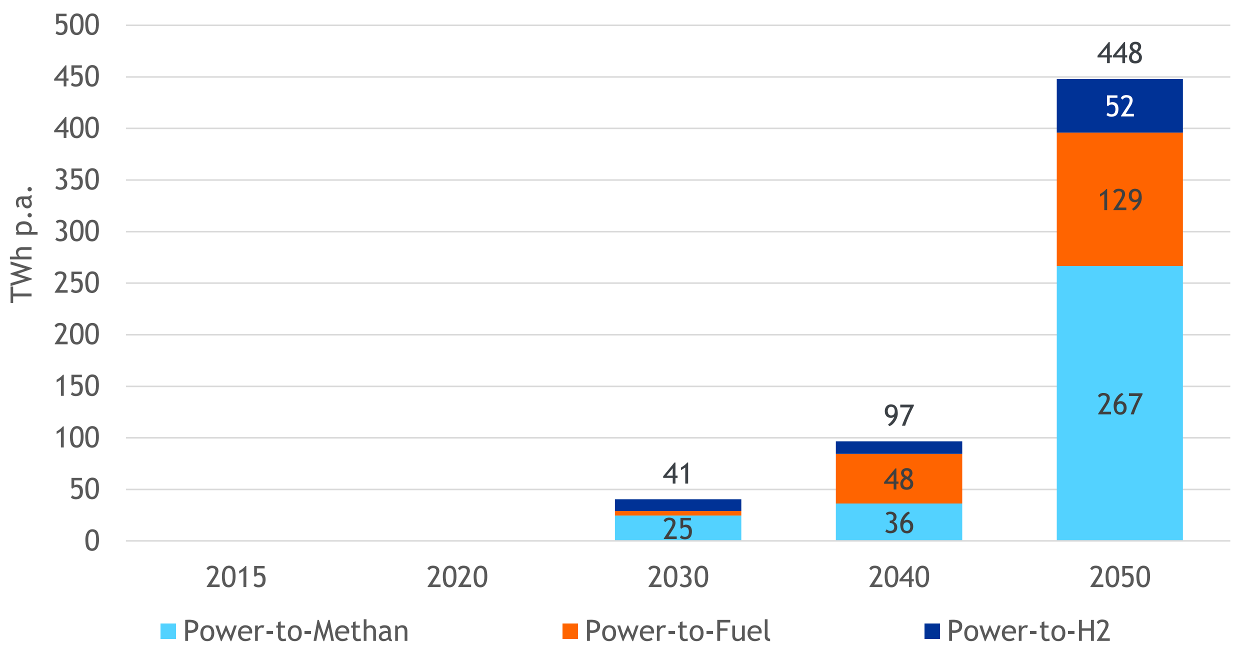

FIGURE 16: USE OF SYNTHETIC FUELS BY FUEL TYPE IN THE REVOLUTION SCENARIO

Due to production efficiency losses, large quantities of electricity generated with zero emissions are required to produce the specified quantities of synthetic fuels. Since Germany possesses limited potential land area for renewables, while a high direct electricity demand, e.g. for heat pumps, is assumed in the Revolution scenario, the necessary quantity of synthetic fuels cannot be produced domestically. Consequently synthetic fuels must be imported to achieve the 95% target.

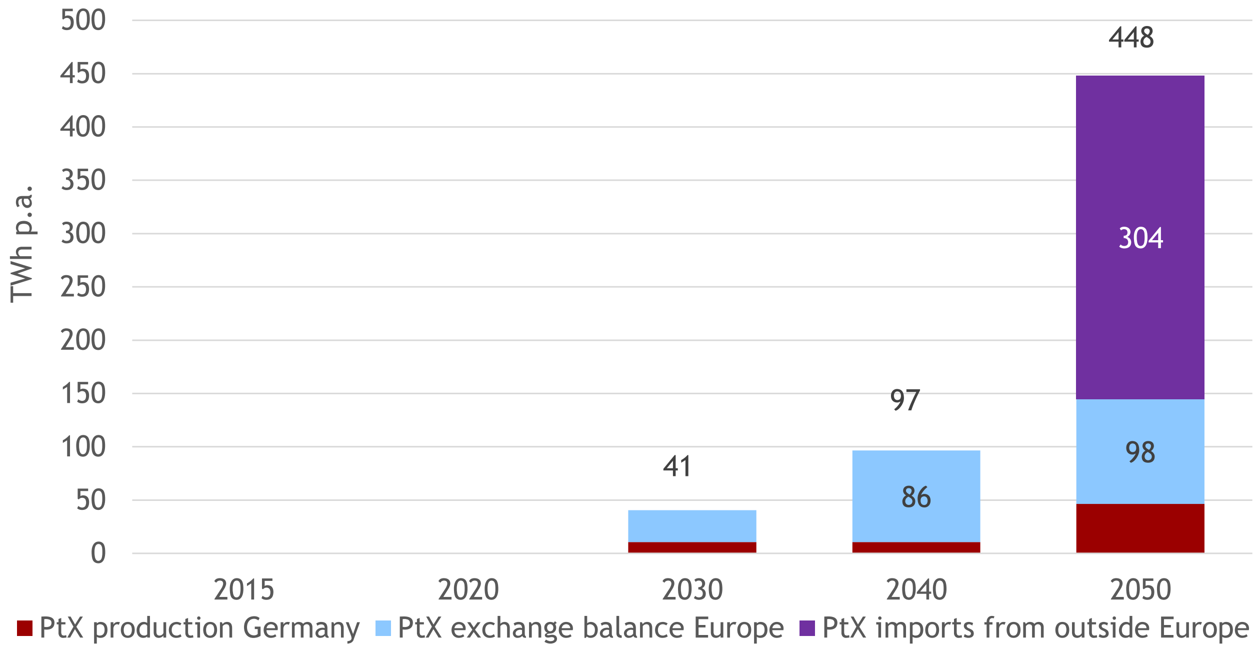

FIGURE 17: GEOGRAPHIC ORIGIN OF SYNTHETIC FUELS IN THE REVOLUTION SCENARIO

As can be seen in Figure 17, only a small proportion of demand is actually produced in Germany, most of it being imported from other European countries and from outside Europe. However, due to the Europe-wide climate targets, the potential for imports from other European countries is limited and is 98 TWh in 2050. Conversely, at a figure of 304 TWh, a much larger quantity of synthetic fuels is imported from countries outside Europe. These are e.g. synthetic fuels produced in North Africa using large-scale solar installations and then transported to Europe by ship or via pipelines.

This aspect of the model might raise concerns, since the need to import synthetic fuels will presumably increase Germany's dependence on imports from abroad. However, the comparative variable should be the total amount of final energy imported by Germany. Imported final energy for the years 2015 and 2050 is represented in Figure 18. It would appear that the increase in imports of synthetic fuels is more than offset by the reduction in imports of other fuels. Other fuels include uranium and also fossil fuels such as oil, gas and hard coal. This portion of energetic imports will fall by more than 90% by 2050, thereby reducing Germany's dependence upon imports.

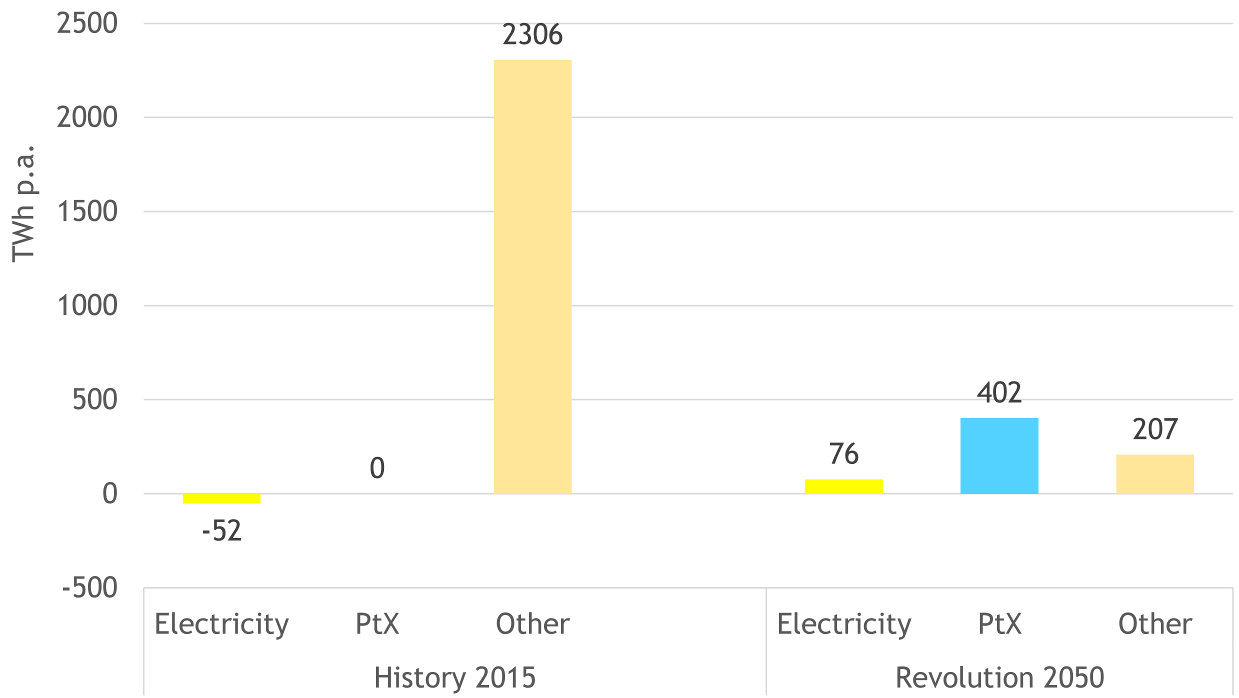

FIGURE 18: ENERGY IMPORTS[7] TO GERMANY IN 2015 AND 2050 IN THE REVOLUTION SCENARIO

2.6 Costs

The development outlined in the Revolution scenario will lead to changes in both the structure and level of costs for German energy provision. The analysed costs essentially fall into three categories:

1. "Direct annual expenditure on energy conversion and consumption" comprises fixed costs for maintenance and operation, fuel costs and costs for electricity imports and Power-to-X imports. This category includes costs for the operation and maintenance of energy-producing and energy-consuming installations excluding any infrastructure.[8]
2. These costs must be distinguished from annual investments for energy producers and consumers, made for long-lasting assets such as power stations, wind turbines or heating systems. Annual investments take the form of a one-off payment and can be converted into annual capital costs by an annuity computation.[9]
3. Costs for energy infrastructure such as gas or electricity networks include capital costs, as well as fixed and variable operating costs for the networks. Future investments in network infrastructure has already been converted into capital costs.

[7] Electricity and Power-to-X in final energy, others in primary energy. The historical data is based on the evaluation tables for Germany's energy balance from AG Energiebilanzen and have been adjusted to exclude non-energy-related consumption.

[8] Due to the absence of data and the marked heterogeneity of individual plants, operating costs of industrial facilities cannot be reliably quantified.

[9] Due to the absence of data and the marked heterogeneity of non-residential buildings and industrial facilities, investment costs for the same cannot be reliably quantified and are not considered in this study.

2.6.1 Direct annual expenditure on energy conversion and energy consumption

2017 TO 2030[10]

As illustrated in Figure 19, direct annual expenditure on energy conversion and energy consumption rises from €98.7 billion in 2017 to €109.6 billion in 2030. A sharply increasing electricity demand and stricter national CO_2 requirements lead to a significant increase in electricity imports, which explain around 45% of the additional costs (+€4.9 billion). The Power-to-X imports required to meet the CO_2 target in 2030 cost a further €5.1 billion. Operating and maintenance costs increase slightly (+€2.4 billion). Fuel costs are driven by two opposing effects. On the one hand, the demand for fossil and biogenic fuels drops between 2017 and 2030 by around 2,850 TWh/a to 1,850 TWh/a (-35.1%). This is due to greater energy efficiency, an increasing proportion of renewables, increasing electricity imports and the use of synthetic fuels. This is offset by an increase in fuel prices, emerging from "WEO New Policies 2016" calculations. The quantity effect more than offsets the price effect, resulting in a slight drop in the cost of fuels (-€1.5 billion).

2030 TO 2050

The structure of direct annual expenditure on energy conversion and energy consumption changes fundamentally between 2030 and 2050. Fuel costs, which in 2030 account for nearly 60% of all costs clearly attributable to a year, drop from €64.1 billion in 2030 to €14.4 billion in 2050, equating to a drop of 78%. There are several reasons for this: firstly, the energy consumer sectors Buildings, Industry and Transport become more efficient and more widely electrified, so that their demand for conventional primary energy sources drops sharply. The residual demand for conventional energy sources is largely covered by synthetic fuels in 2050, in order to achieve the national CO_2 reduction target. These fuels are either imported or produced in Germany. Moreover, the electricity produced in Germany is practically carbon-neutral. This is due to the massive expansion of wind and solar energy and also to the use of synthetic gas in gas-fired power stations. However, this means that costs for Power-to-X imports will increase by 788% between 2030 and 2050, to a figure of €40.2 billion. At approximately €54.6 billion, total energy costs for conventional, biogenic and synthetic Power-to-X energy carriers are approximately €11 billion lower in 2050 than in 2017, due to the decline in energy consumption resulting from improved energy efficiency in energy conversion facilities and consumer plants. Costs for electricity imports will triple between 2030 and 2050. This can be attributed in equal amounts to rising electricity prices and increasing electricity imports. Imports are necessary because of the national CO_2 provisions, which are stricter than the EU-ETS provisions throughout the rest of Europe and the lack of potential for producing more electricity from renewables in Germany due to spatial constraints. Fixed costs for operation and maintenance do not change to any notable extent between 2030 and 2050 (-€0.4 billion). Total direct annual costs fall slightly from €110 billion in 2030 to €105 billion in 2050. This analysis does not include any capital costs. These arise indirectly as a result of annuating investments, which are discussed below.

[10] In each case, the costs considered in the cost analysis are those that arise after 2017. Costs that arise between 2015 and 2017 are not considered and are not therefore represented.

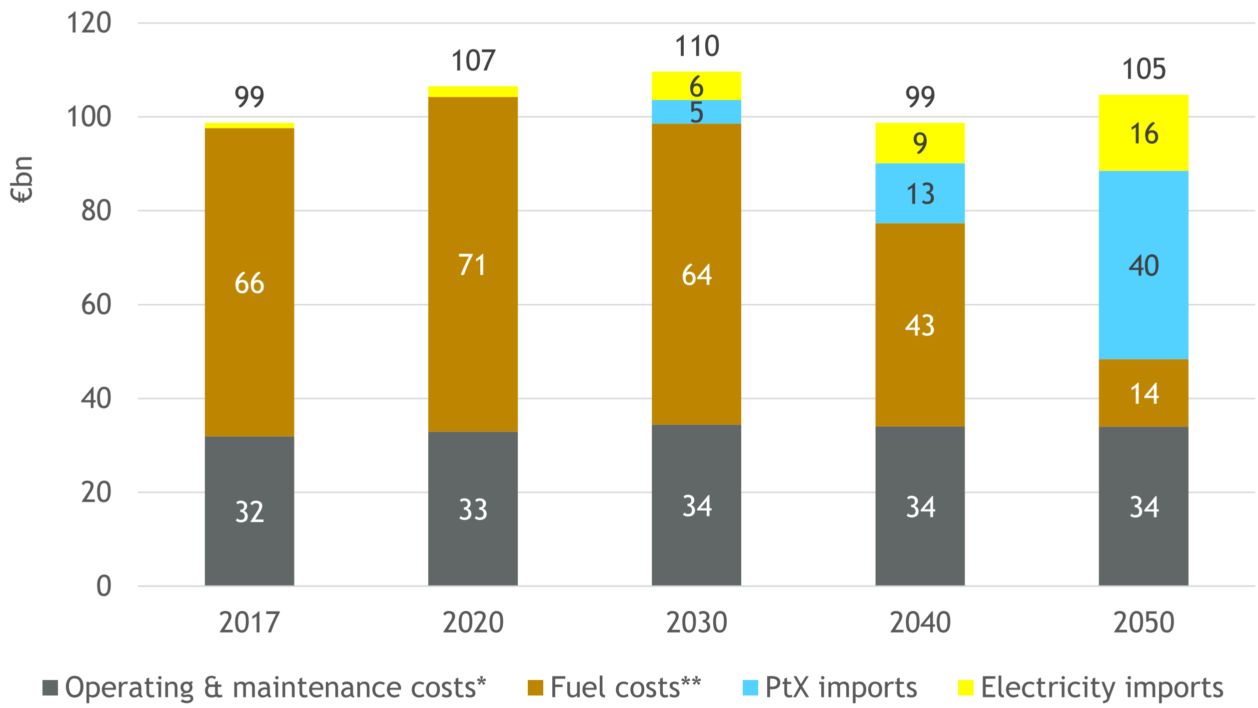

FIGURE 19: DIRECT ANNUAL EXPENDITURE ON ENERGY CONVERSION AND CONSUMPTION IN THE REVOLUTION SCENARIO[11]

2.6.2 Investment costs

Investment costs are represented in the model for the Buildings and Transport sectors as well as the Energy industry. Since development of the Transport sector is assumed to be exogenous and identical in both the scenarios considered, this will not be discussed in any more detail. Due to the greater heterogeneity of individual machines and plants and the lack of available data, investment costs in the Industry sector cannot be represented with any degree of accuracy. Investment costs are shown in Figure 20.

2017 TO 2030[12]

In the Revolution scenario, investment costs in the Buildings sector are determined by regulatory requirements relating to the number of installed heat pumps and renovation rates. Up until 2030, this means that investment in building insulation and heating systems is more or less constant. It is around €17 billion in 2017 and also in 2030. Around half the costs are attributable to insulation and the other half to heating costs. Investment in the Energy sector will primarily be driven by the CO_2 target. Based on the assumption of an EU-ETS with rising carbon prices and hence stricter CO_2 targets by 2030, there is increasing investment in renewable energies. This means that investment costs in the Energy industry will increase by 75% between 2017 and 2030, notably from €8.2 billion to €14 billion.

[11] * Operating and maintenance costs for power stations, Power-to-X plants, renewable plants, building insulation and heating systems.
** Costs for conventional and biogenic fuels.
[12] Investment costs are only considered after the year 2020, since this is the first year in the considered timeframe, in which investment can be made in new facilities (power stations, heating systems, etc.).

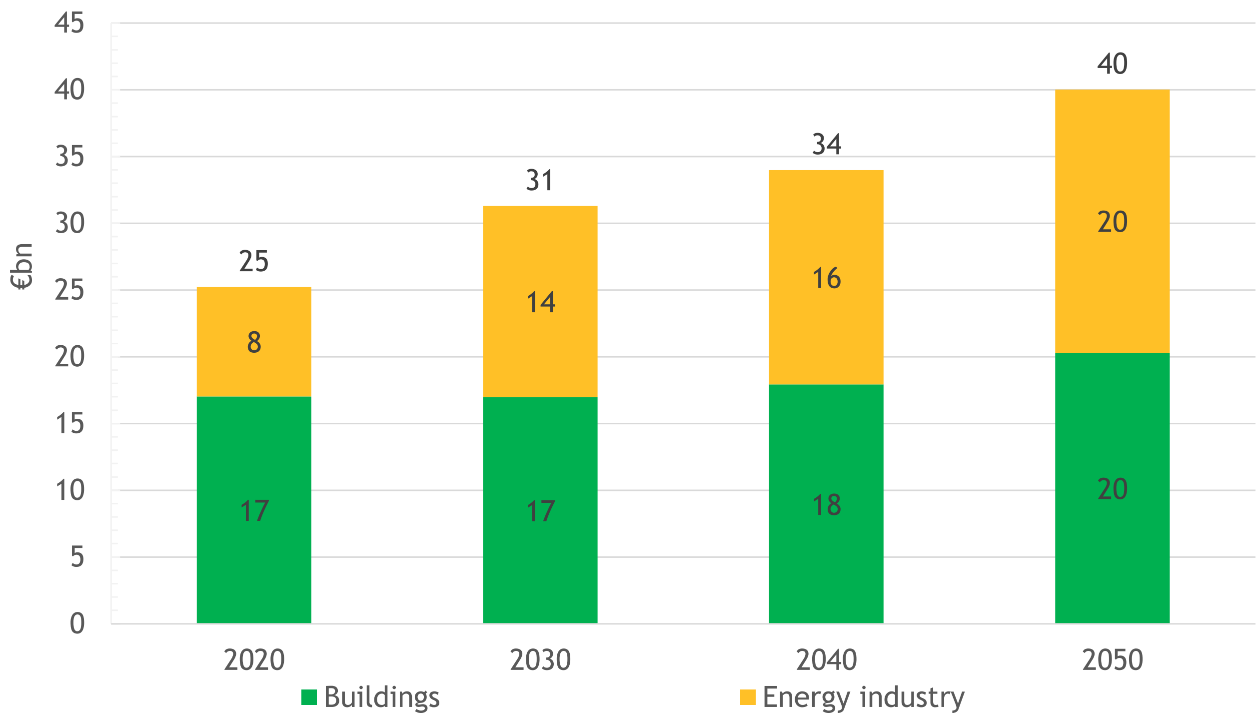

FIGURE 20: ANNUAL INVESTMENT IN THE BUILDINGS AND ENERGY INDUSTRY SECTORS IN THE REVOLUTION SCENARIO

2030 TO 2050

The mandatory installation of heat pumps will continue in the Building sector between 2030 and 2050. Since renovation rates will still not exceed the prescribed 2%, renovation costs will remain more or less constant. There is a further increase in investment costs in the Energy sector. This is partially due to an increased rate of expansion of renewable plants. Since the potential limits of less expensive technologies are increasingly exhausted, it is also necessary to invest more in more expensive technologies. In addition to this, the increase in peak load and the limited availability of renewable plants will necessitate the expansion of gas-fired power stations.

2.6.3 Network costs

Network costs include annual costs for electricity, gas and heat infrastructure. In addition to various other factors, power and gas network are expanded as required, based on the respective demand. Costs for heat networks are represented on the basis of a simplified approach. A detailed description of the respective methodology, the sources used and the detailed results can be found in Appendix 2. Annual network costs are shown in Figure 21.

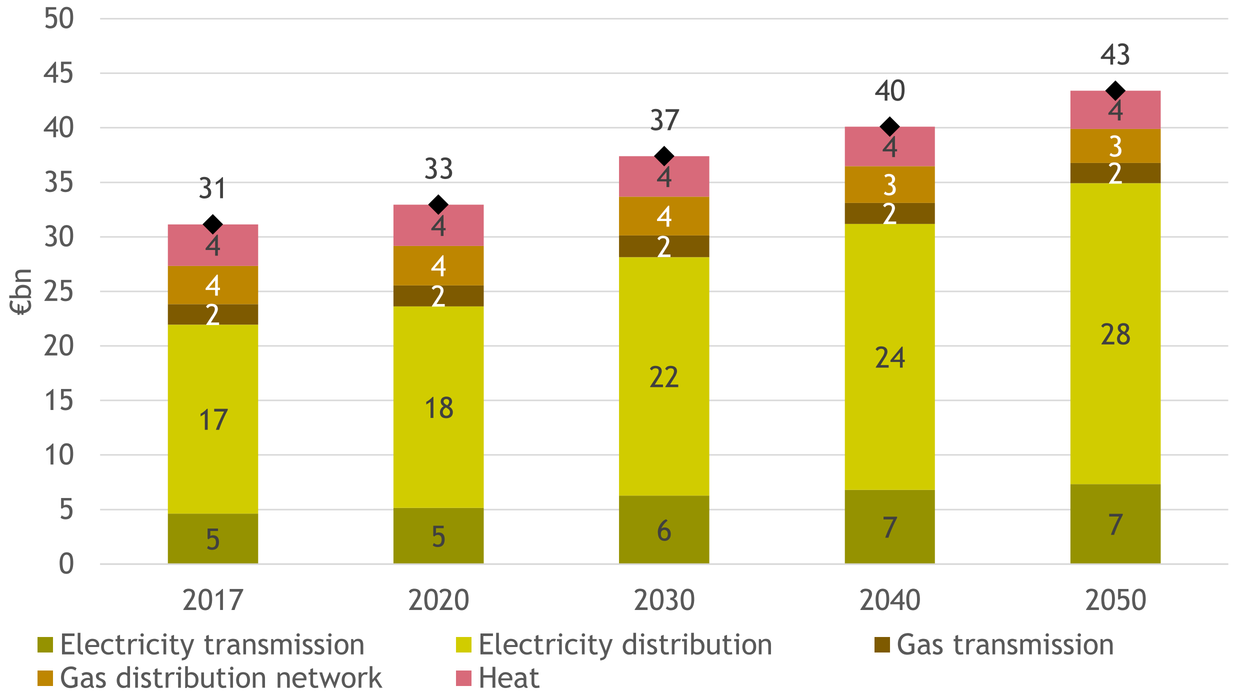

FIGURE 21: ANNUAL COSTS OF ELECTRICITY, GAS AND HEAT NETWORKS IN THE REVOLUTION SCENARIO

2017 TO 2030

Network costs will increase by €31.2 billion between 2017 and 2030 to €37.4 billion. This cost increase is almost exclusively due to rising electricity network costs. Additional costs will arise for the transmission network and particularly for the distribution network. Due to the 37 GW expansion of wind and solar energy by 2030, transmission networks will have to be greatly expanded, giving rise to additional annual costs of €1.7 billion (from €4.6 billion in 2017 to €6.3 billion in 2030). However, the greatest proportion of additional costs is incurred for the distribution grid. For this alone, there are additional annual costs of €4.5 billion by 2030 (from €17.3 billion in 2017 to €21.8 billion in 2030). The increase in peak load due to heat pumps and electric cars on the one hand and the increased installation of solar roof panels and onshore wind will require a massive expansion of the distribution grid. On the other hand, costs for gas infrastructure will only increase by €0.2 billion by 2030, to €5.6 billion. This cost increase is due to the investments enshrined in NEP 2016, which are necessary because of a change in the distribution of demand within Germany and the changeover from L to H gas. In the Revolution scenario, the demand for local and district heat declines by nearly 10% to 100 TWh in 2030. However, due to the higher fixed costs for heat infrastructures, costs will only drop by €0.1 billion by 2030, namely to €3.7 billion.

2030 TO 2050

The above trend continues between 2030 and 2050. Over this period, net costs increase by a further €6 billion to €43.4 billion. These additional costs are solely due to further increases in the cost of electricity infrastructure. The continuing expansion of renewable energies and the further spread of heat pumps and electric cars will mean that additional expansion of the transmission and distribution network is required. Specifically, the costs for the transmission network increase from €6.3 billion to €7.3 billion and costs for the distribution network from €21.8 billion to €27.6 billion. In the Revolution scenario, annual costs for gas infrastructure fall slightly by €0.2 billion between 2030 and 2050. Due to declining demand from household customers and business, the quantities of gas transported decrease, particularly in the distribution network. An estimate based on information from transmission and distribution network operators shows dismantling costs of approximately €10.6 billion. If these costs are equally distributed over the years between 2030 and 2050, one obtains costs that are €0.3 billion higher than in 2030.

2.7 Repercussions on gas distribution and heat networks

Due to the focus on GHD reduction by electrification in the Revolution scenario, the demand for heat and gas will decline significantly in this scenario over the coming 30 years, particularly in distribution networks. This chapter examines the repercussions on gas and heat customers, as well as on operators of these networks, using example distribution networks.

2.7.1 Gas distribution networks

The impacts on gas distribution network operators and their customers are examined on the basis of two networks. One of these networks has a high proportion of household customers (Network H) while the other has a high proportion of industrial customers (Network I). In order to illustrate these effects as simply as possible, the annual output of both networks is 1,000 GWh for the year 2017. It is assumed that the development of the demand quantities for the individual customer groups (Household, Business and Industry) of the example networks corresponds to the changes in demand determined in the model. The network costs of both networks correspond to average network costs, so that the costs of an example network that covers the total demand, would correspond to the total costs described in Chapter 2.6.3. This means that the cost development of the example network includes a proportionate amount of the costs that arise from changing over from L to H gas in distribution networks. Furthermore, the network costs are broken down on the basis of a contract-price-based tariff. The ratio of network charges for Household, Business and Industry customers is based on information from the BNetzA Monitoringbericht 2016 [monitoring report by the Federal Network Agency] about the current ratio of network charges. Dismantling costs are not included in the considered network charges, since it is not clear whether remaining network users would have to bear these costs in their network charges and to which years these would be assigned. The development of gas demand and costs in the example networks is shown in Figure 22. The corresponding development of network charges can be found in Figure 23.

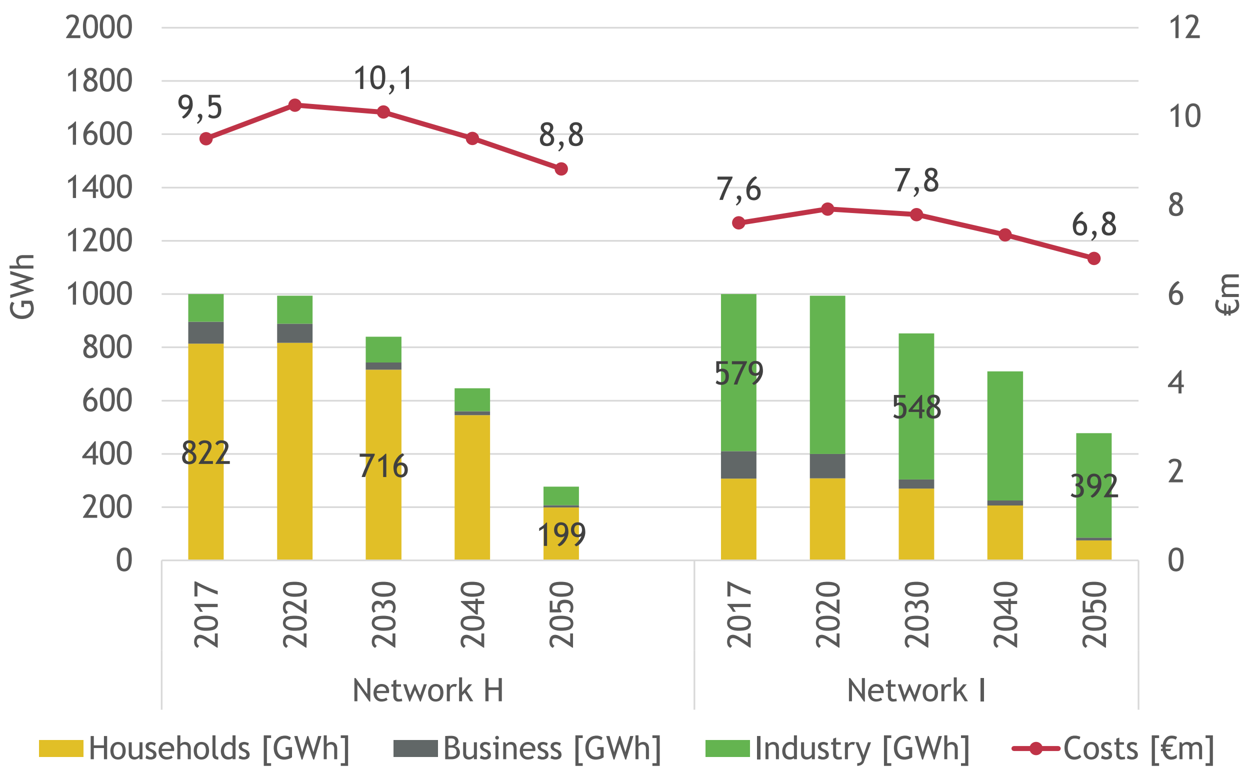

FIGURE 22: DEVELOPMENT OF DEMAND AND COSTS IN EXAMPLE GAS NETWORKS IN THE REVOLUTION SCENARIO

2017 TO 2030

Between 2017 and 2030, gas demand drops by a good 15% in both in "Network H" dominated by household customers and also in "Network I" dominated by industry. In addition to this, slight cost increases are assumed for both example networks, due to the fact that they must include a proportion of the costs for converting from L gas to H gas. However, even in a network with no investment over this period, there would only be slight cost reductions, since the majority of costs are capital costs for pre-existing operating costs and quantity-related operating costs. As a result of the drop in demand, combined with the increase in costs, network charges (distribution network share) have to rise by approximately 20% in both networks over this period, in order to completely cover the network operator's costs. Network charges for household customers rise from 1.06 to nearly 1.3 €ct/kWh. These networks charge rises could force some gas customers to change over to electricity-based technologies, thereby exacerbating the decline in demand. If network charges were to remain at the 2017 level, this would mean the loss of 19% of costs in "Network H" (€1.9 million) and 20% of costs in "Network I" (€1.5 million).

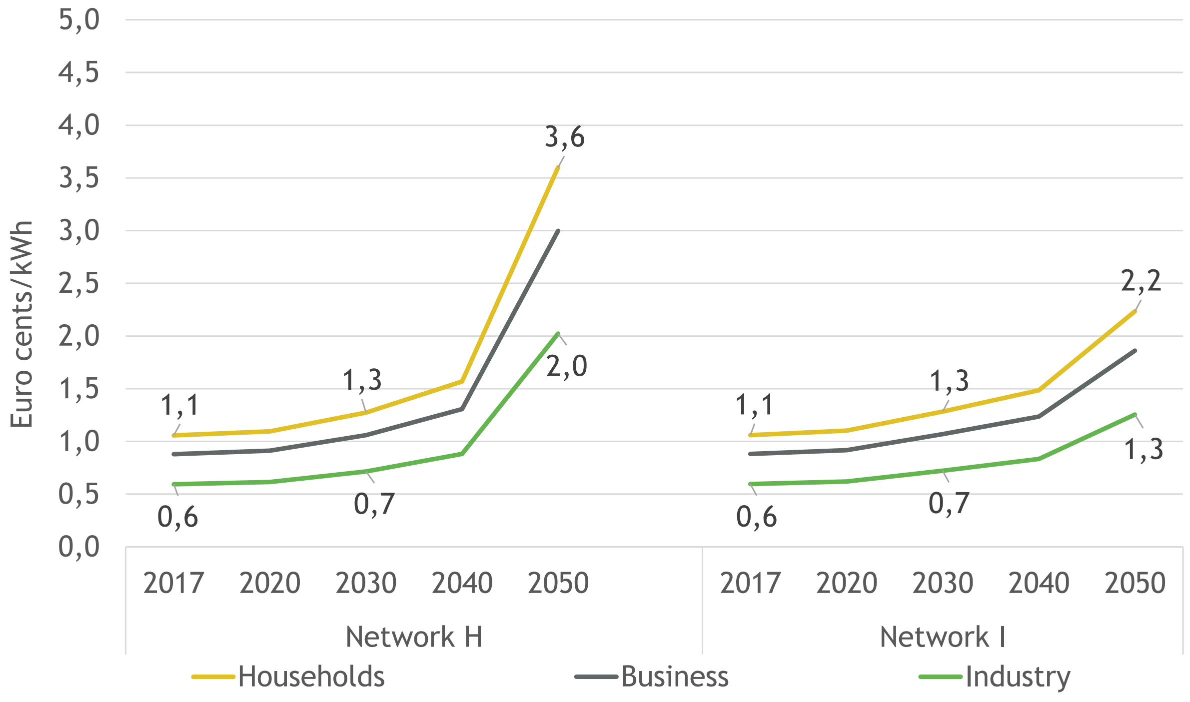

FIGURE 23: DEVELOPMENT OF NETWORK CHARGES IN EXAMPLE GAS NETWORKS IN THE REVOLUTION SCENARIO

2030 TO 2050

In the Revolution scenario, there are even greater drops in demand between 2030 and 2050. Compared with 2030, gas demand will fall by 67% in "Network H" and by 44% in "Network I". Compared with the current value (2017), gas demand will fall by as much as 73% in "Network H" and by 53% in "Network I". However, since infrastructure costs are largely driven by capital costs and fixed operating costs, there will hardly be any reduction in costs between 2030 and 2050. Specifically, they will fall from €10.1 billion to €8.8 billion in "Network H" and from €7.8 billion to €6.8 billion in "Network I". As a consequence, the necessary network charges will have to increase massively in both networks, in order to cover the operators' costs. In the network dominated by industrial customers, network charges will have to increase by 70% relative to 2030 and by 100% relative to 2017, in order to cover costs. Industrial customers who cannot replace gas by electricity, would experience serious competitive disadvantages. For other industries, it would be worth changing over to power-based technologies, which would then push up network charges even higher for remaining customers and would even force them out of the market. The costs spiral that this would initiate might even jeopardise the economic viability of the entire gas distribution network. Passing on the potential costs of dismantling sections of the network that are no longer required to the remaining gas consumers would further aggravate the situation. In the "Network H" dominated by household customers, network charges triple between 2030 and 2050. Such an extreme cost increase would presumably encourage some of the remaining households to replace gas heating systems by heat pumps, so that the customers that were left would then have to absorb even higher network charges. DIMENSION+ calculations, in which the network charges for heating systems constitute endogenous variables, reveal that such a cost spiral is initiated in the Revolution scenario. The result of this is that no gas heating is used after the year 2050. Here again, the redistribution of dismantling costs onto gas consumers would further aggravate the situation. In the Revolution scenario, operators of a distribution network dominated by household customers would therefore have to be prepared for the fact that they could no longer (profitably) operate their gas networks and might even have to dismantle them completely after 2050. If charges were to be kept at a constant level, barely half of the costs (46%) could be covered in "Network H" and less than one third of the costs (29%) in "Network I". In the example networks this would lead to losses of €6.3 million (Network H) and €3.7 million (Network I) respectively.

2.7.2 Heat networks

Apart from a decline in the demand for gas, in the Revolution scenario there is also a significantly reduced demand for district and local heating in the Building sector. For the purposes of this analysis, the impact of the decline in demand for district and local heat on the revenue and costs of heating network operators are investigated using a hugely simplified example network. This example network has a demand of 100 GWh in 2017. The pattern of demand in the example network corresponds to the pattern of overall demand for district and local heating in the Building sector, determined in the Revolution scenario. The network costs correspond to the average costs obtained for heat networks in the scenario. Unlike gas networks, heat networks are not regulated, so that operators can orient their price to match that of competing heating systems. In order to analyse the development of the revenue situation, it is assumed for simplicity that the putative heat network operator budgets for a charge of 5 €ct/kWh. The development of demand, costs and revenues for heat networks are shown in Figure 24.

2017 TO 2030

Demand for district and local heating will fall by 21% between 2017 and 2030. If prices remain the same, there is an equivalent decline in profits. However, due to the high proportion of capital and fixed operating costs, there is only a slight reduction in costs. This results in a drop in profit of €0.8 billion for the operator of the example network. It is possible that revenues will exceed total capital and operating costs and that investments will have to be partially depreciated. In order to maintain a constant profit, the operator would have to increase prices for use of district and local heat by nearly 21%. Since the purchasing costs for consumers in the Building sector are currently very low and the costs of converting to other heating systems are very high, this will probably not trigger a spiral of decline and price increases.

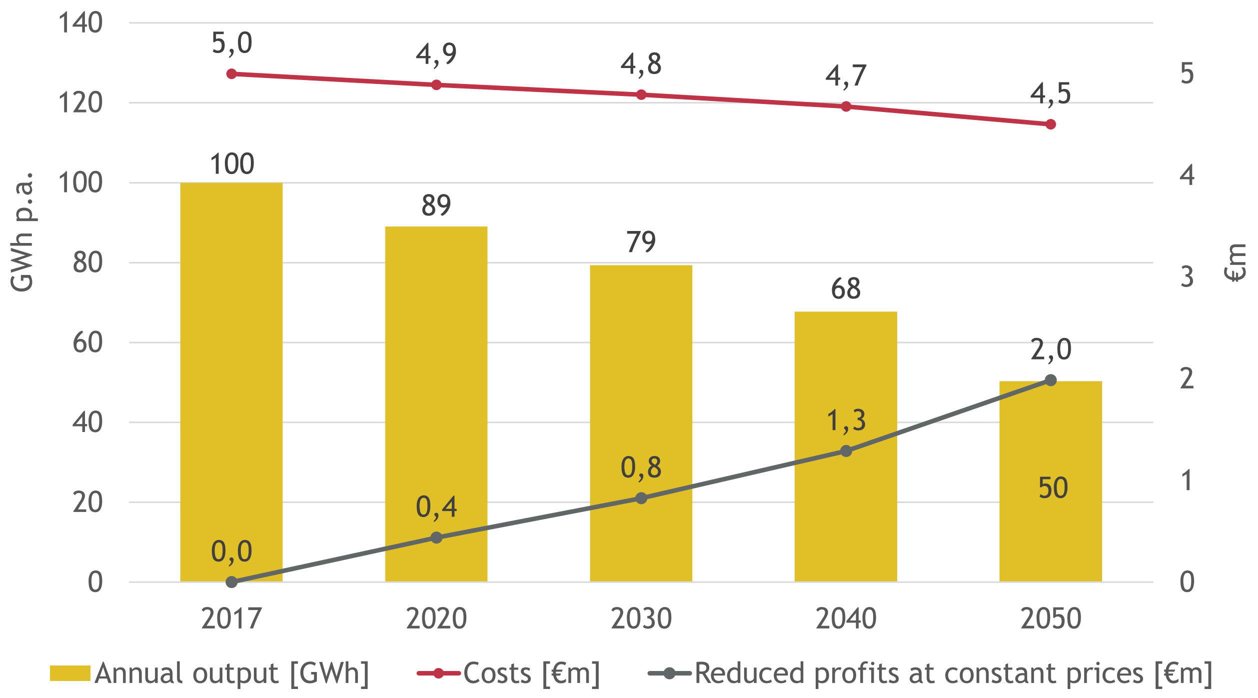

FIGURE 24: DEVELOPMENT OF DEMAND, COSTS AND REVENUES IN EXAMPLE HEAT NETWORKS IN THE REVOLUTION SCENARIO

2030 TO 2050

Between 2030 and 2050 there is a further drop in demand of 37% relative to 2030 and 50% relative to 2017. If prices are maintained, these drops are mirrored by revenues. As during the years 2017 to 2030, costs hardly decrease, due to the high proportion of fixed costs. The example network operator's profits fall by a further €1.2 million relative to 2030 and €2 million relative to 2017. It is likely that revenue will exceed total capital and operating costs and investments will have to be partially or completely depreciated. In order to maintain a constant profit level, the operator would have to increase prices for using district and local heat by 48% relative to 2030 and by 79% relative to 2017. It is conceivable that, in the face of such a huge price rise, customers swap over to other technologies. In this case, operators could not offset the drop in demand by charging higher prices.

3 EVOLUTION SCENARIO

3.1 Definition of the scenario

The Evolution scenario is based on an openness to all technologies. Consequently, greenhouse gas reduction in the energy supply sector is implemented without any politically defined technology preferences. Existing infrastructure and plants are used as effectively as possible to achieve the cheapest possible avoidance of CO_2 emissions.

In the Evolution scenario, the model does not include any regulatory requirements for installed heating technology in the Building sector. The installation of heating systems and building insulation are endogenously determined in the model, so as to identify the minimum-cost pathway to transformation of the Building sector. In contrast to the Revolution scenario, greater potential for district and local heat connections is assumed, since there is no competitive pressure due to politically enforced expansion of heat pumps.

As in the Building sector, it is assumed that greenhouse gas reduction is achieved in the Industry sector without any bias towards any particular technology. Consequently, in contrast to the Revolution scenario, there are no statutory requirements for electrification of process heat production. Conversely, it is assumed that the Transport sector, which is only peripherally considered in this study, will follow the same transformation pathway as in the Revolution scenario.

3.2 Development of GHG emissions

In the Evolution scenario, the emission targets defined in the Klimaschutzplan are also achieved in keeping with the target assumptions. Figure 25 shows the temporal course of GHG emissions. The main difference from the Revolution scenario is therefore that the targets are achieved without favouring any specific technology. One obtains a different sectoral breakdown of residual GHG emissions, since the reduction targets for 2030 and 2050 are defined as cross-sector targets in this study. The results show that, in 2050, 27 million t CO_2 equivalent are emitted in the Industry sector and 15 million t CO_2 equivalent in the Building sector. At a figure of 1 million t CO_2 equivalent, the energy supply is virtually emission-free in 2050. In the Evolution scenario, with no technology bias, more greenhouse gas is emitted in the Building sector and less in the Industry sector than in the Revolution scenario. The difference is 7 million t in the Building sector and 6 million t in the Industry sector. The following sections outline the detailed background to these modelling results for the individual sectors.

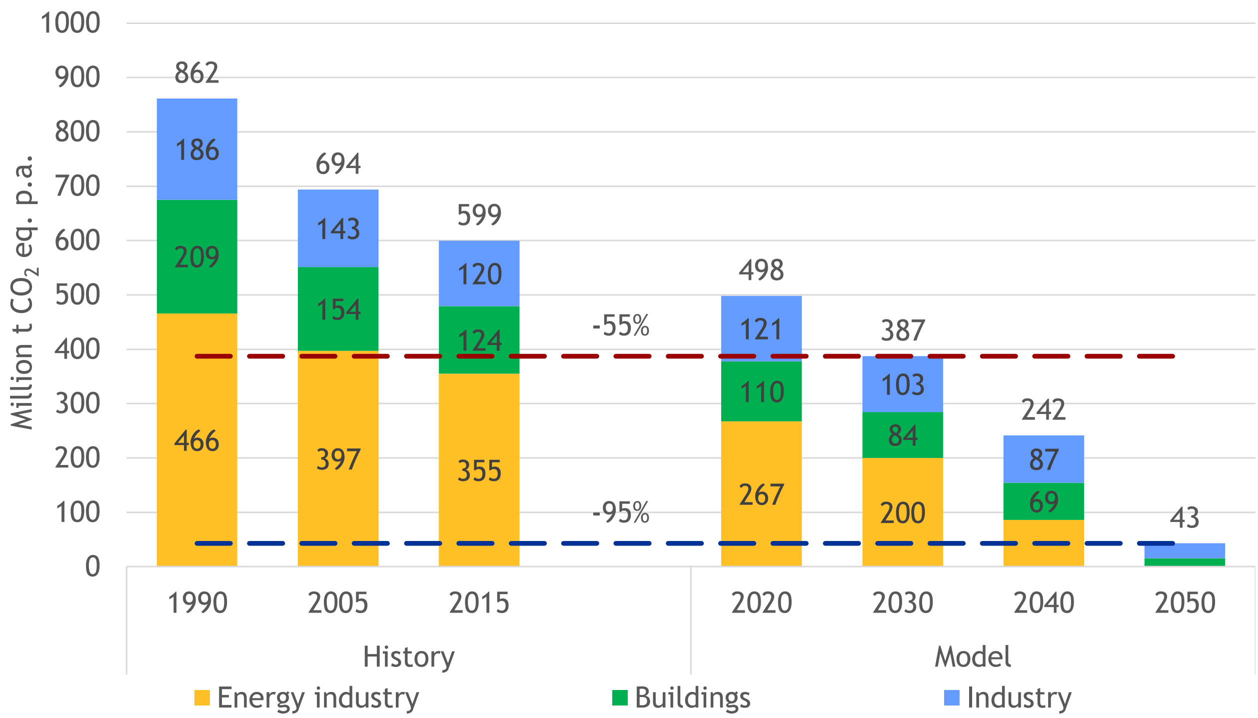

FIGURE 25: DEVELOPMENT OF GHG EMISSIONS IN THE EVOLUTION SCENARIO

3.3 Final energy demand

3.3.1 Building sector

2017 TO 2030

In the Evolution scenario, greenhouse gases are reduced in the Building sector without favouring any particular technology. This produces a fundamentally different mix of technologies for heating residential buildings than in the Revolution scenario. Old oil-fired heating systems are primarily replaced by modern gas heating systems by 2030. District heat is also used to some extent to heat residential buildings. This means that 11 million gas heating systems are installed in 2030, thus increasing their market share. In contrast, in 2030 the proportion of heat pumps in the technology mix is negligible, at a similar level to today. The development of installed heating technologies in residential buildings in the Evolution scenario is schematically represented in Figure 26.

Due to the lack of technology bias in the Evolution scenario, the insulation measures that are implemented also differ from those in the Revolution scenario. This is particularly related to the special requirements for building insulation to allow a heat pump to operate efficiently. Consequently, due to the predominant installation of gas heating in the Evolution scenario, less insulation is needed. Figure 27 shows the final energy consumption for space heating and hot water in the Building sector resulting from insulation and technology mix, broken down according to different energy carriers. The total energy demand in the Building sector falls to 636 TWh by 2030. Thus final energy consumption in 2030 is 86 TWh higher than in the Revolution scenario. However, also in the non-technology-specific Evolution scenario, insulation measures combined with greater efficiency of heating systems lead to a reduction in final energy demand in 2030 of 16% relative to 2015. Because of better insulation, gas demand falls by 50 TWh to a total of 329 TWh in 2030.

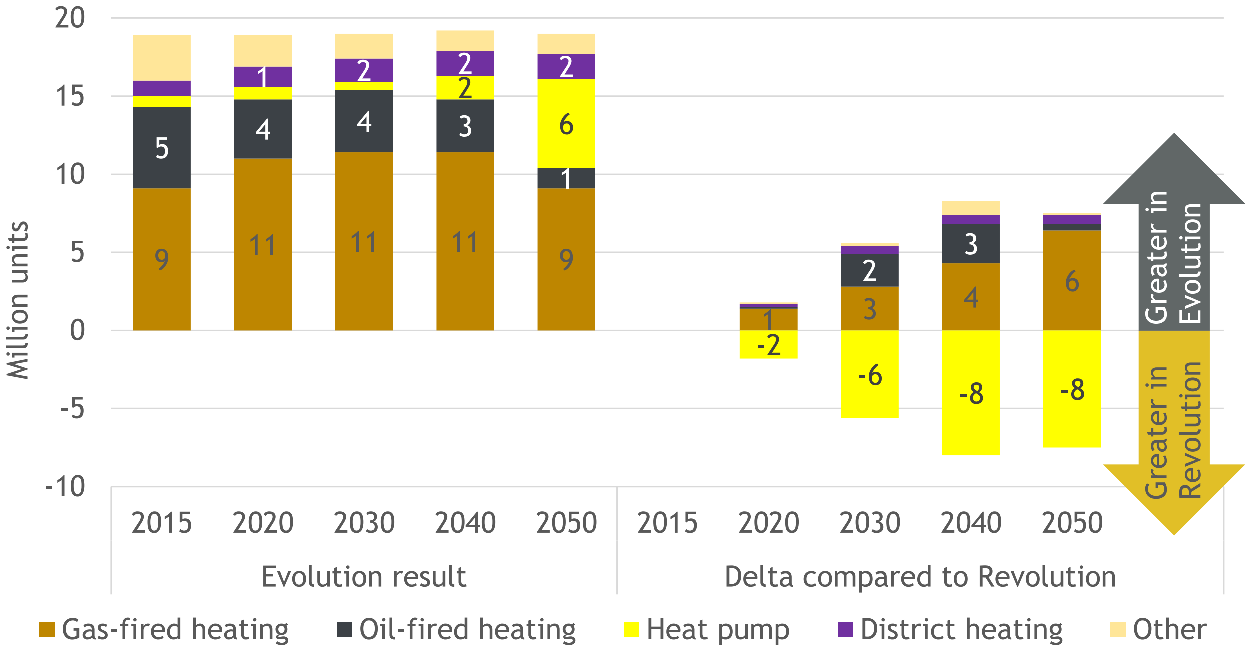

FIGURE 26: HEATING TECHNOLOGIES IN RESIDENTIAL BUILDINGS IN THE EVOLUTION SCENARIO

2030 TO 2050

After 2030, the development of installed heating technologies is quite different, since the number of heat pumps increases. By 2050, the number of heat pumps installed in residential buildings increases to 6 million. The number of gas heating systems falls slightly to 9 million. Despite the increased use of heat pumps in 2050, 7 million fewer units are installed than in the Revolution scenario. This difference is largely driven by capital costs for equipment and insulation, as well as the infrastructure costs required for connecting to the network and integrating the heat pumps into the power supply system. Apart from the costs for network expansion, the increasing peak load that has to be covered by guaranteed capacity, plays a decisive role.

Total energy demand in the Building sector falls to 423 TWh by 2050. Due to inferior insulation and the use of other heating systems, it is therefore 150 TWh higher than in the Revolution scenario. Nevertheless, insulation measures also play an important part in greenhouse gas reduction in the Building sector in the non-technology-specific scenario. In the Evolution scenario, gas is still the most important energy carrier for heat generation in 2050.

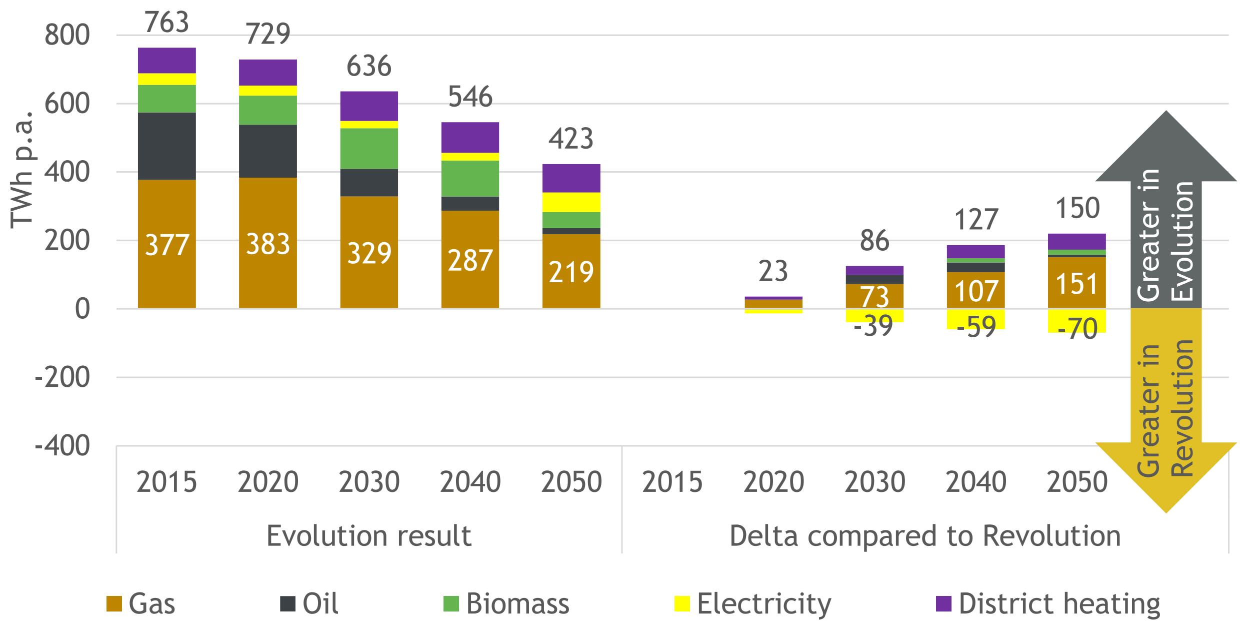

FIGURE 27: FINAL ENERGY DEMAND FOR SPACE HEATING AND HOT WATER IN BUILDINGS IN THE EVOLUTION SCENARIO

3.3.2 Industry sector

2017 TO 2030

In the Evolution scenario, final energy demand in the Industry sector initially remains more or less constant up until 2030. The difference between the Evolution and Revolution scenarios is comparatively small in the Industry sector up until 2030, since swapping fuels is relatively difficult to achieve, due to the complex structure of the production processes. Electricity demand by Industry will increase to 386 TWh by 2030. Accordingly, gas demand will drop slightly to 213 TWh. Figure 28 schematically illustrates the development of industrial energy demand.

2030 TO 2050

Even in the Evolution scenario, there is greater electrification of industrial processes by 2050, resulting in increasing electricity demand and declining gas demand. The absolute electricity demand in the Industry sector is 433 TWh in 2050, gas demand is 191 TWh. However, the degree of electrification is significantly lower in the Evolution scenario than in the Revolution scenario. Consequently, in the Evolution scenario, industrial electricity demand in 2050 is 88 TWh lower.

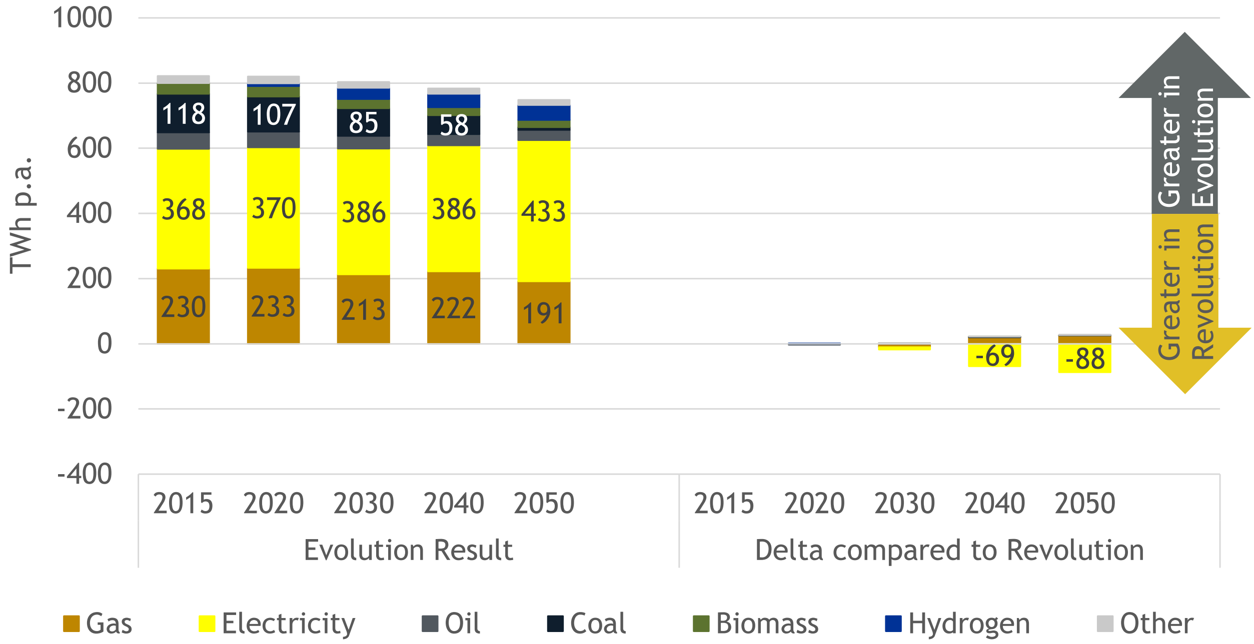

FIGURE 28: DEVELOPMENT OF FINAL ENERGY DEMAND IN THE INDUSTRIAL SECTOR IN THE EVOLUTION SCENARIO

3.4 Electricity sector

3.4.1 Net electricity demand and net electricity production

2017 TO 2030

Net electricity demand also increases by 2030 in the Evolution scenario. However, at a demand of 656 TWh in 2030, this rise is less marked than in the Revolution scenario. The difference between the scenarios in 2030 is 64 TWh. Increasing electricity demand is primarily due to the Transport sector, where electricity demand increases by 75 TWh. Electricity demand also increases in the Industry sector, while demand declines slightly in the Building sector.

The structural changes in electricity generation that emerge in the Evolution scenario are similar to those in the Revolution scenario. Electricity generation from renewables increases sharply over time, representing 67% of total net power production in 2030. As in the Revolution scenario, onshore wind power is the main energy carrier, generating 205 TWh of electricity in 2030. Electricity generation from offshore wind and PV also increases to 54 TWh and 85 TWh respectively in 2030.

As a result of the phase-out of nuclear energy and the gradual reduction in the use of coal for electricity production (also due to the assumed national climate targets), conventional energy production declines significantly over the period under consideration. Overall net electricity production remains more or less constant up until 2030, at 622 TWh, making it significantly lower than in the Revolution scenario. Figure 29 schematically illustrates the course of net electricity production in the Evolution Scenario.

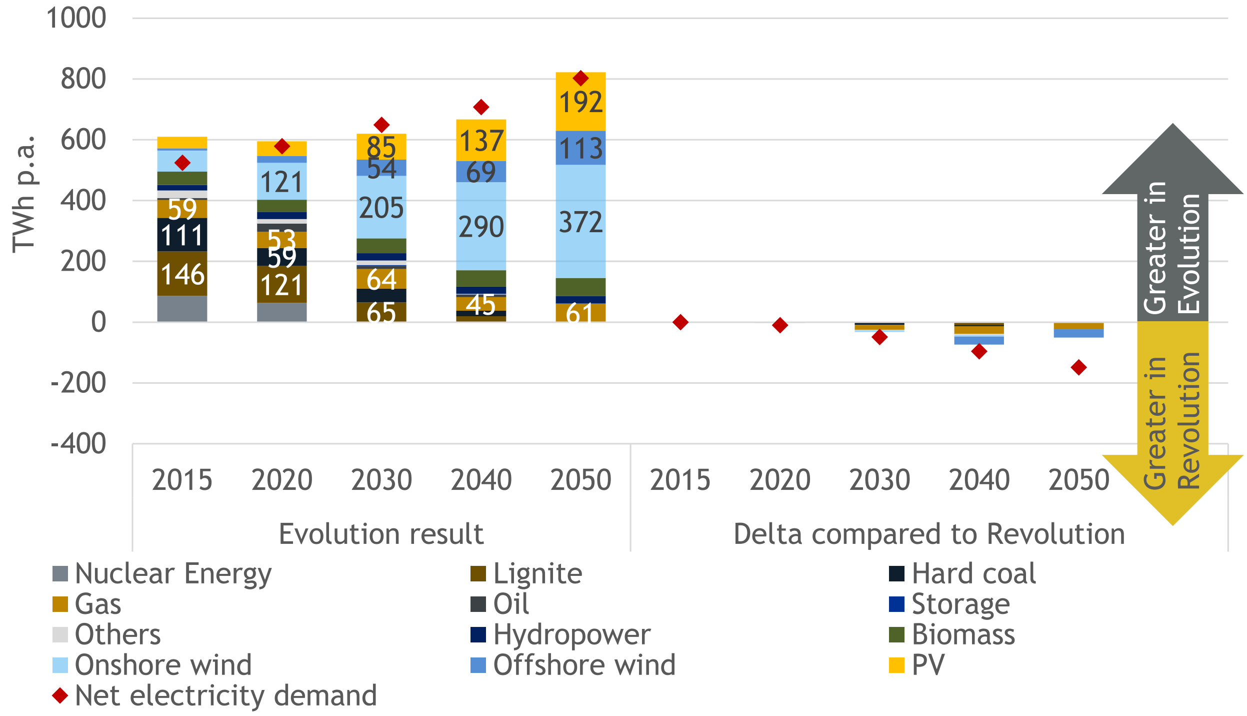

FIGURE 29: NET ELECTRICITY GENERATION IN THE EVOLUTION SCENARIO

2030 TO 2050

In the period after 2030, net electricity demand continues to increase to 811 TWh in 2050. However, due to less extensive electrification in the Evolution scenario, electricity demand in 2050 is 148 TWh lower than in the Revolution scenario. This difference is down to lower electricity demand in Industry and the Building sector in the Evolution scenario, since these sectors use fewer electricity-based technologies.

Electricity generation from renewables continues to increase sharply up until 2050. In 2050, generation from onshore wind power is 372 TWh, generation from offshore wind power 113 TWh and generation from PV is 192 TWh. In 2050, generation from offshore wind is lower than in the Revolution scenario, while generation from onshore wind and PV is the same in both scenarios. The percentage of total net electricity generation that comes from renewables increases to 92% by 2050.

Up until 2050, the development in the conventional power station fleet is the same as in the Revolution scenario. Electricity generation from coal declines and is replaced by gas-based electricity generation. By 2050, gas is the only remaining conventional energy source in the generation mix. However, due to the lower overall electricity demand, at a figure of 61 TWh, less gas-based electricity generation is required than in the Revolution scenario. All gas-based electricity generation uses synthetic gas.

3.4.2 Power stations

2017 TO 2030

The increase in electricity generation from renewables requires a big expansion of domestic generation capacities. The installed capacity of onshore wind power increases to 99 GW by 2030. Hence, onshore wind power is expanded to a similar extent as in the Revolution scenario. The installed capacity of offshore wind and PV also develops in the Evolution scenario in the same way as in the Revolution scenario. In 2030, installed capacity for offshore wind power is 15 GW and 89 GW for PV. Figure 30 represents the results graphically.

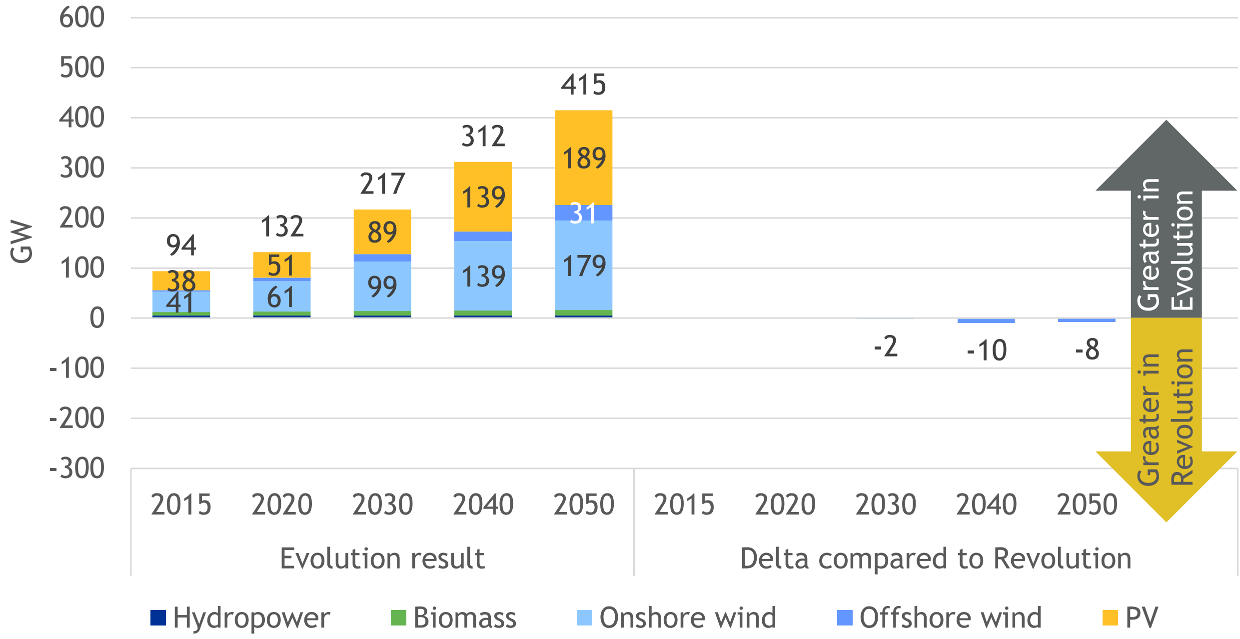

FIGURE 30: INSTALLED CAPACITY OF RENEWABLE ENERGIES IN THE EVOLUTION SCENARIO

Even in the Evolution scenario, conventional power stations see a gradual restructuring to gas-based back-up power stations that can provide inexpensive guaranteed capacity. However, because of the lower electricity demand, much less back-up capacity needs to be installed than in the Revolution scenario. The total installed capacity of gas-fired power stations initially increases from 31 GW in 2015 to 60 GW in 2030. In 2030, there is therefore 19 GW less gas-based generation capacity installed in the Evolution scenario than in the Revolution scenario. The installed capacity of coal-fired power stations also falls sharply over time in the Evolution scenario to a level of 9 GW for hard coal and coal respectively in 2030. Total installed conventional power station capacity is 80 GW in 2030. The results are schematically represented in Figure 31.

The differences in guaranteed capacity between the Evolution and Revolution scenarios are a result of the different development in electricity demand, resulting in different requirements for guaranteed capacity. Figure 32 represents the corresponding demand for peak load, broken down according to the considered sectors. Due to the absence of any technology barriers in the Evolution scenario and the associated predominance of gas-based heating technologies in buildings, peak load resulting from the Building sector declines by 2030. This results in an 18 GW difference in peak load between the two scenarios in 2030. Conversely, there is no difference in peak load in Industry by 2030. Due to the exogenously modelled development, the required guaranteed capacity in the Transport sector is identical in both considered scenarios, increasing to 14 GW in 2030. Thus aggregated peak load in the Evolution scenario is 92 GW in 2030. This means that, in 2030, total demand for guaranteed capacity is 18 GW lower than in the Revolution scenario.

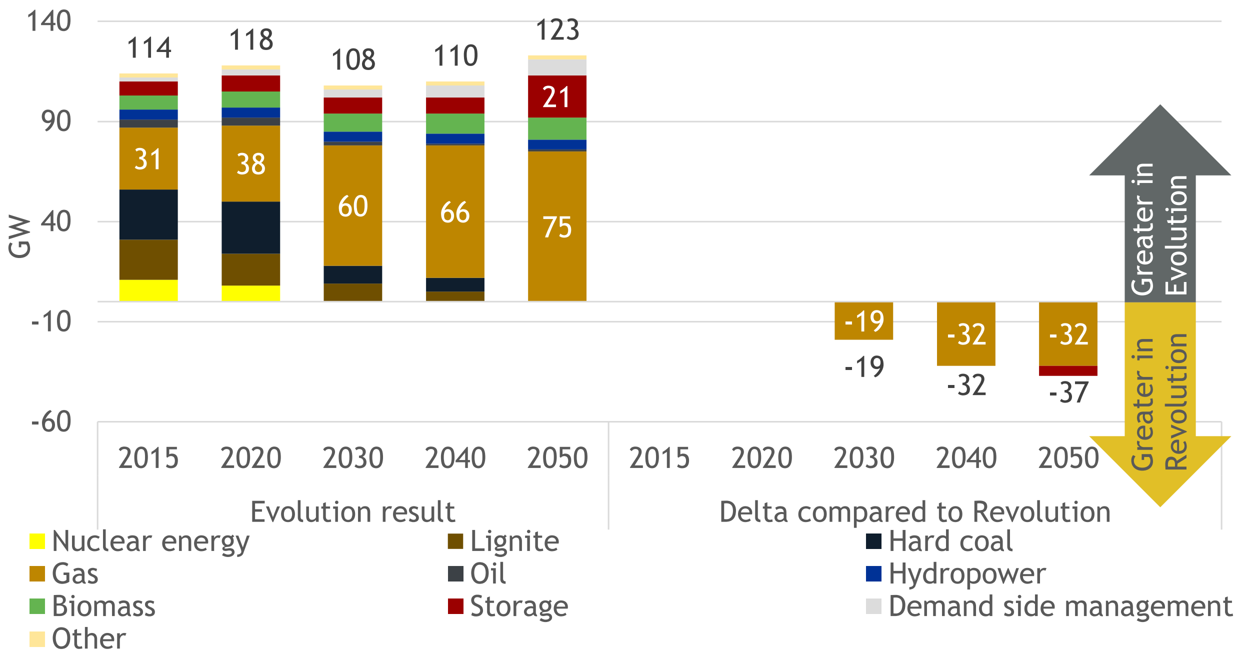

FIGURE 31: DEVELOPMENT OF CONVENTIONAL POWER STATIONS IN THE EVOLUTION SCENARIO

2030 TO 2050

The expansion of electricity generating capacity based on renewables continues after 2030. Onshore wind power is expanded to 179 GW, offshore wind to 31 GW and PV to 189 GW. Consequently, the assumed limits of potential areas available for onshore wind farms in Germany is also completely exhausted in the Evolution scenario. Also in the case of PV, all locations in central and southern Germany are used. Hence the only difference relative to the Revolution scenario is to be found in offshore wind power. Installed capacity is 8 GW lower in the Evolution scenario.

Among the conventional power stations fleet, gas-fired power stations will continue to be expanded after 2030. In 2050, the installed capacity is 75 GW. As a result of lower electricity demand and correspondingly lower peak load, this value is significantly lower than in the Revolution scenario. The difference is 32 GW. As in the Revolution scenario, coal-fired power stations will also disappear completely from the German power station fleet by 2050.

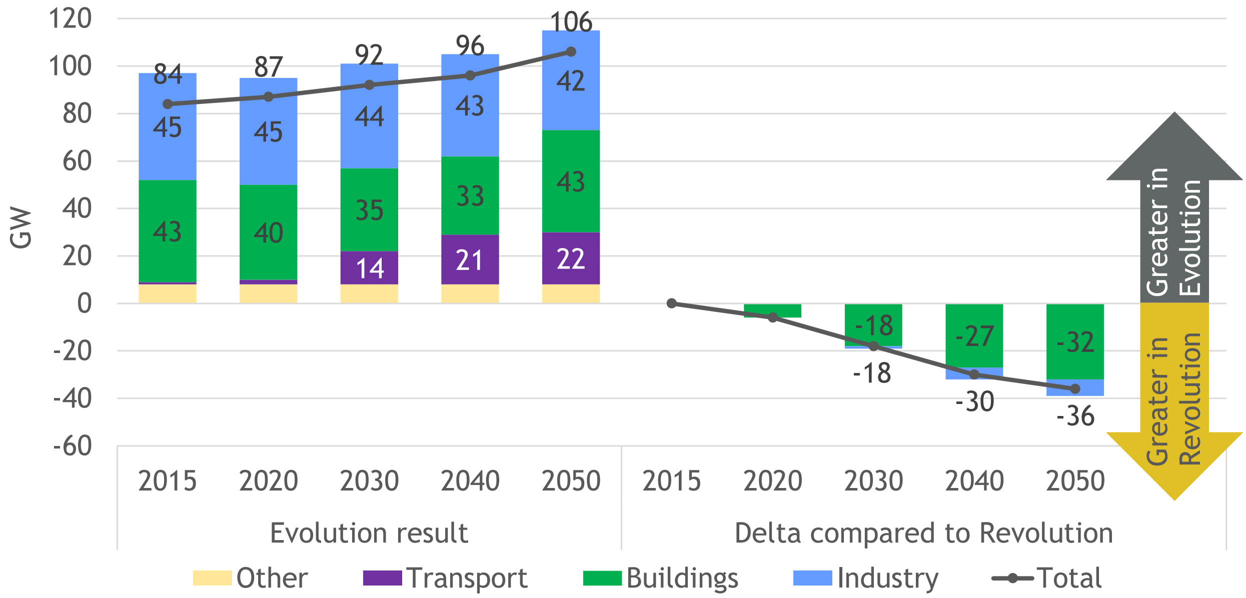

FIGURE 32: DEVELOPMENT OF PEAK LOAD IN THE EVOLUTION SCENARIO

The peak load in the German electricity supply system increases to 106 GW by 2050. This means that the peak load is 36 GW lower in the Revolution scenario. This difference is due to the lower peak loads in the Buildings and Industry sectors, where less use is made of electricity-based technologies. As in the Revolution scenario, total peak load is lower than the sum of the individual sectors for simultaneity reasons.

3.4.3 External electricity trading

2017 TO 2030

Net electricity imports increase by 2030 due to the phase-out of nuclear power and a decline in domestic conventional electricity generation. Germany becomes a net electricity importer as early as 2030. However, net imports in 2030 are significantly lower than in the Revolution scenario. The difference is 16 TWh in 2030. This difference is due to the lower electricity demand in the Evolution scenario, which therefore requires fewer electricity imports to cover German electricity demand. The results are schematically represented in Figure 33.

Figure 34 illustrates the rest of the European electricity market. Generation from renewables also increases sharply in Europe in the Evolution scenario, almost doubling by 2030. This is offset by a marked reduction in generation from hard coal (-42% compared with 2015), gas (-54%) and oil (-47%) in the period up until 2030.

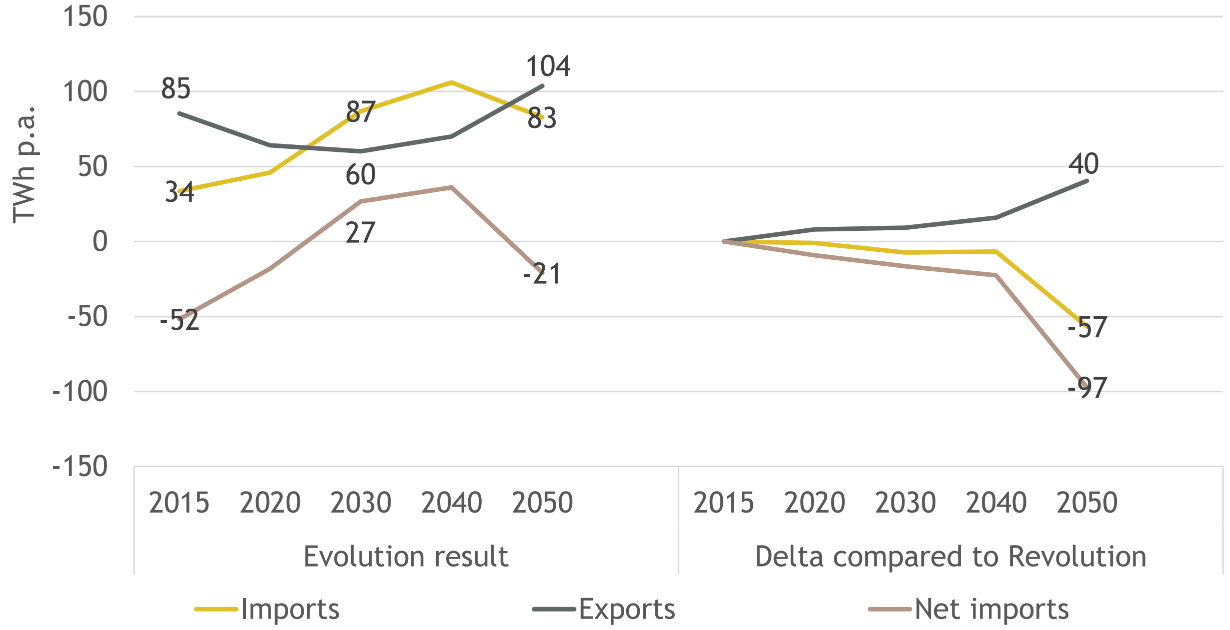

FIGURE 33: DEVELOPMENT OF EXTERNAL ELECTRICITY TRADING IN THE EVOLUTION SCENARIO

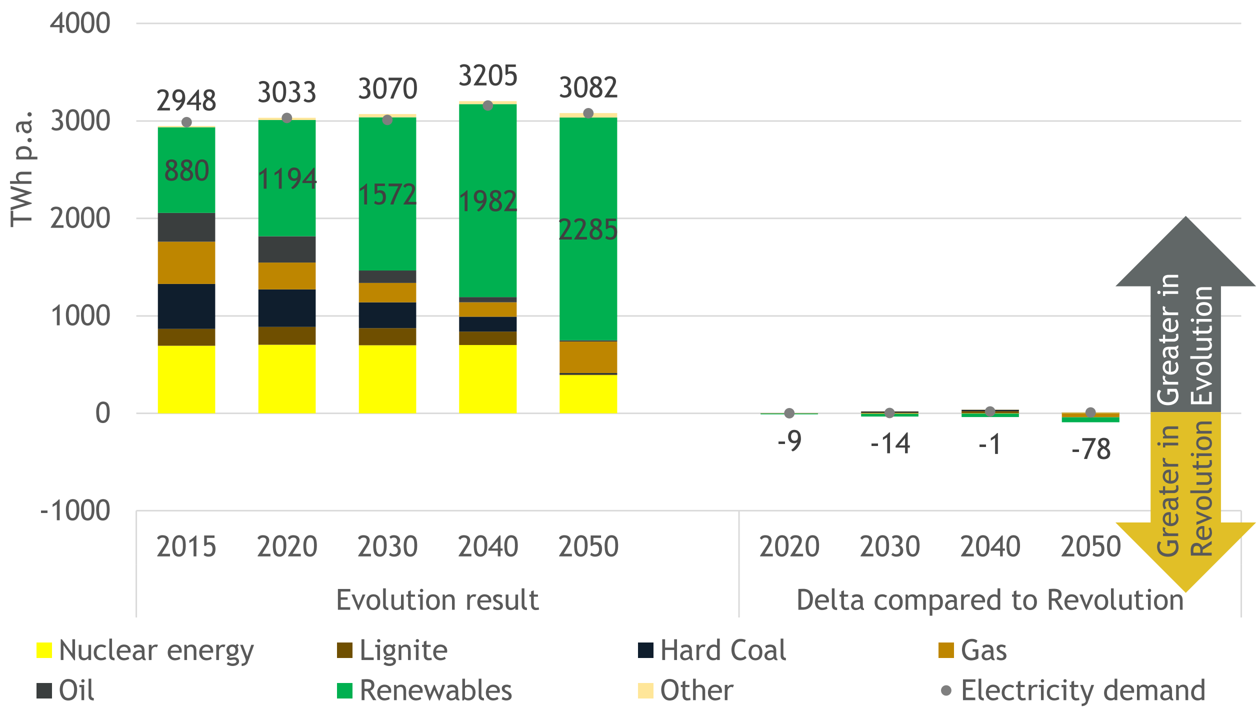

FIGURE 34: DEVELOPMENT OF EUROPEAN ELECTRICITY GENERATION (EXCLUDING GERMANY) IN THE EVOLUTION SCENARIO[13]

[13] EU 28 excluding Malta and Cyprus, as well as Norway and Switzerland.

2030 TO 2050

First of all there is a slight increase in net electricity imports up until 2040, when they start to decline. This means that by 2050 Germany will once again be a net exporter of electricity. The reason for this development is the high level of electricity generation from renewable sources during hours of high availability of wind and sun, resulting in a surplus of domestic electricity production. This is very different from in the Revolution scenario, in which large quantities of electricity have to be imported, even in 2050, due to the much greater demand for electricity. The difference in net electricity imports between the scenarios is 97 TWh in 2050.
The expansion of renewables also continues in Europe in the period up until 2050, so that generation from renewables increases by 45% between 2030 and 2050. Conversely, in order to meet the much stricter emission targets imposed throughout Europe, conventional generation declines. Generation from coal and oil falls by more than 95% compared with 2015. Generation from gas will only fall by 15% compared with 2015. However, the gas used for electricity generation in 2050 is predominantly synthetic.

3.5 Synthetic fuels

2017 TO 2030

In the Evolution scenario with no particular technology bias, synthetic fuels are a crucial part of the increasingly climate-neutral energy system. In 2030, 10 TWh worth is used in the Industry sector and 31 TWh in the Transport sector. Thus a total of 41 TWh of synthetic fuels is consumed in 2030. This is therefore no different from the Revolution scenario in 2030. The results are schematically represented in Figure 35.

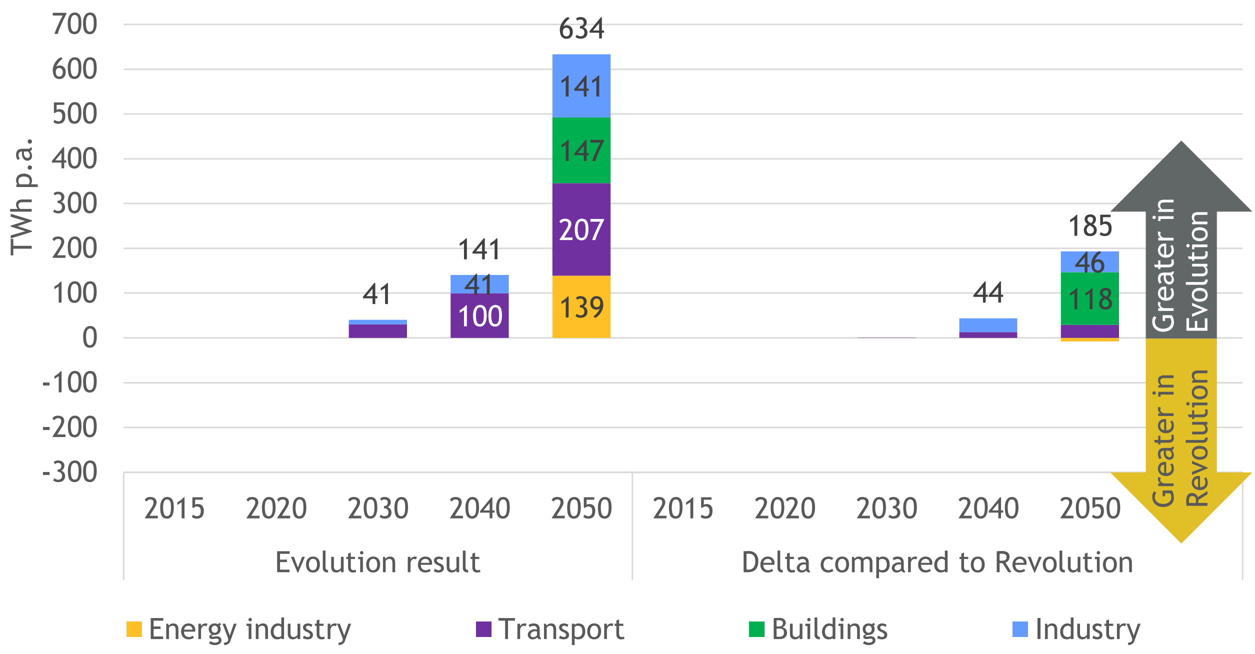

FIGURE 35: USE OF SYNTHETIC FUELS IN THE EVOLUTION SCENARIO

Figure 36 shows the breakdown of demand by different type of fuel. It can be seen from the figure that, even in the Evolution scenario, gas produced by Power-to-Gas technologies makes up the largest proportion of synthetic fuels. The total amount of energy provided by synthetic gas in 2030 is 23 TWh.

Due to the limited availability of potential surface area within Germany for generating electricity from renewable sources, a significant percentage of synthetic fuels are imported from abroad. At a figure of 30 TWh in 2030, most of the demand is covered by imports from the rest of Europe. 11 TWh are produced within Germany. The results are schematically represented in Figure 37.

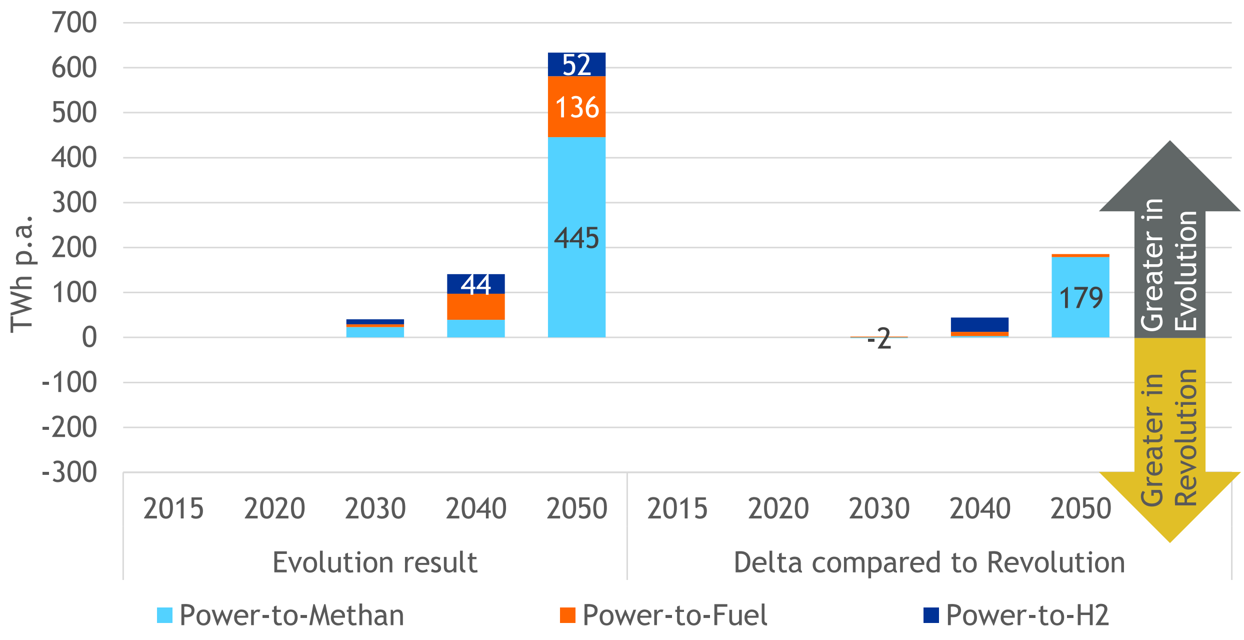

FIGURE 36: USE OF SYNTHETIC FUELS BY TYPE IN THE EVOLUTION SCENARIO

2030 TO 2050

The use of synthetic fuels rises sharply in 2050 to 634 TWh, since the 95% carbon reduction target in all sectors under consideration requires the use of synthetic fuels. With a use of 207 TWh, the Transport sector has the largest proportion, followed by the Building sector at 147 TWh and the Industry sector at 141 TWh. 139 TWh of synthetic fuels will also be used in the energy supply sector in 2050, since the potential surface area of suitable locations for renewable energy generation is limited in Germany, making it impossible to produce sufficient emission-free power directly from renewable sources. The use of synthetic fuels in the Building sector, the Transport sector and the Industry sector is greater in the Evolution scenario than it is in the Revolution scenario. The difference is 118 TWh in the Building sector, 46 TWh in the Industry sector and 29 TWh in the Transport sector. Conversely, consumption in the Energy industry is 8 TWh lower, since, because of heavier consumption in the other sectors, there are more competing uses. Overall this gives a total consumption of 634 TWh of synthetic fuels in 2050. Total consumption is therefore 185 TWh or 41% higher than in the Revolution scenario.

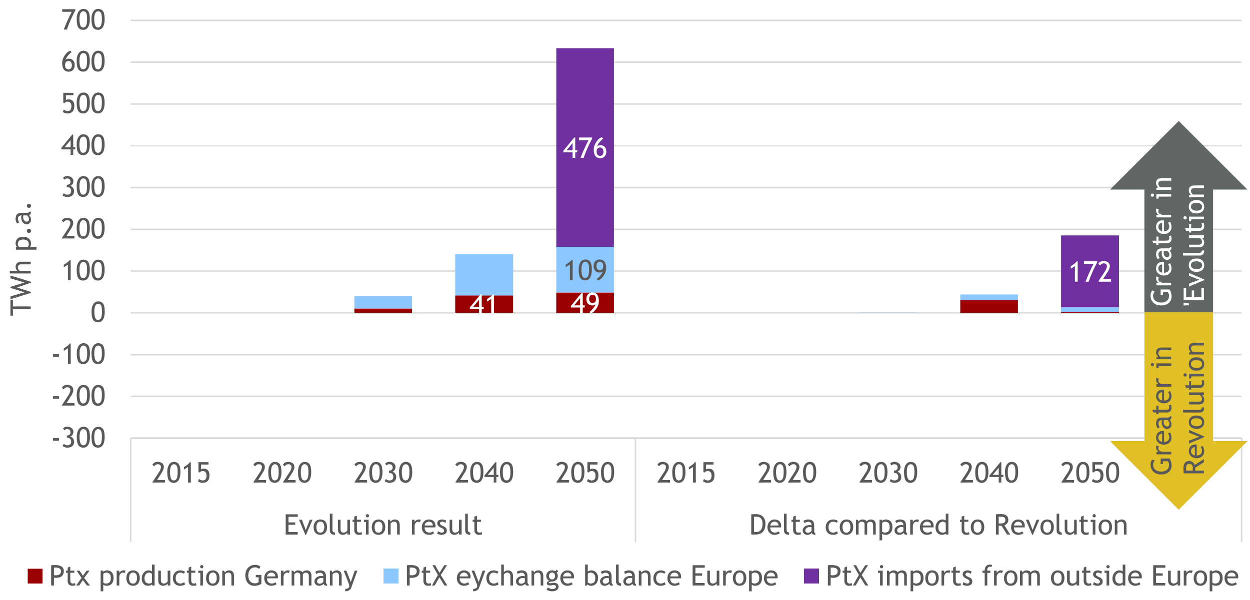

FIGURE 37: GEOGRAPHIC ORIGIN OF SYNTHETIC FUELS IN THE EVOLUTION SCENARIO

At a figure of 445 TWh, the largest proportion of synthetic fuels used in 2050 is synthetic gas. In addition to this, 136 TWh Power-to-Fuel is used in the Transport sector and 52 TWh of synthetic hydrogen in the Industry sector.

In 2050, most of the synthetic fuels that are used are imported from outside Europe, since there is a rapid rise in competing uses for emission-free electricity within Europe. The total amount imported from abroad is 585 TWh. 109 TWh of this comes from the rest of Europe and 476 TWh from outside Europe. 49 TWh are produced within Germany.

If one were to look at imports of synthetic fuels, one could easily gain the impression that Germany becomes more dependent upon energy imports in the Evolution scenario as well. Figure 38 shows Germany's energy imports in the years 2015 and 2050. It appears that energy imports to Germany decline overall in the Evolution scenario too. Although, on the one hand, 183 TWh more synthetic fuels are imported than in the Revolution scenario, on the other, electricity imports are nearly 100 TWh lower.

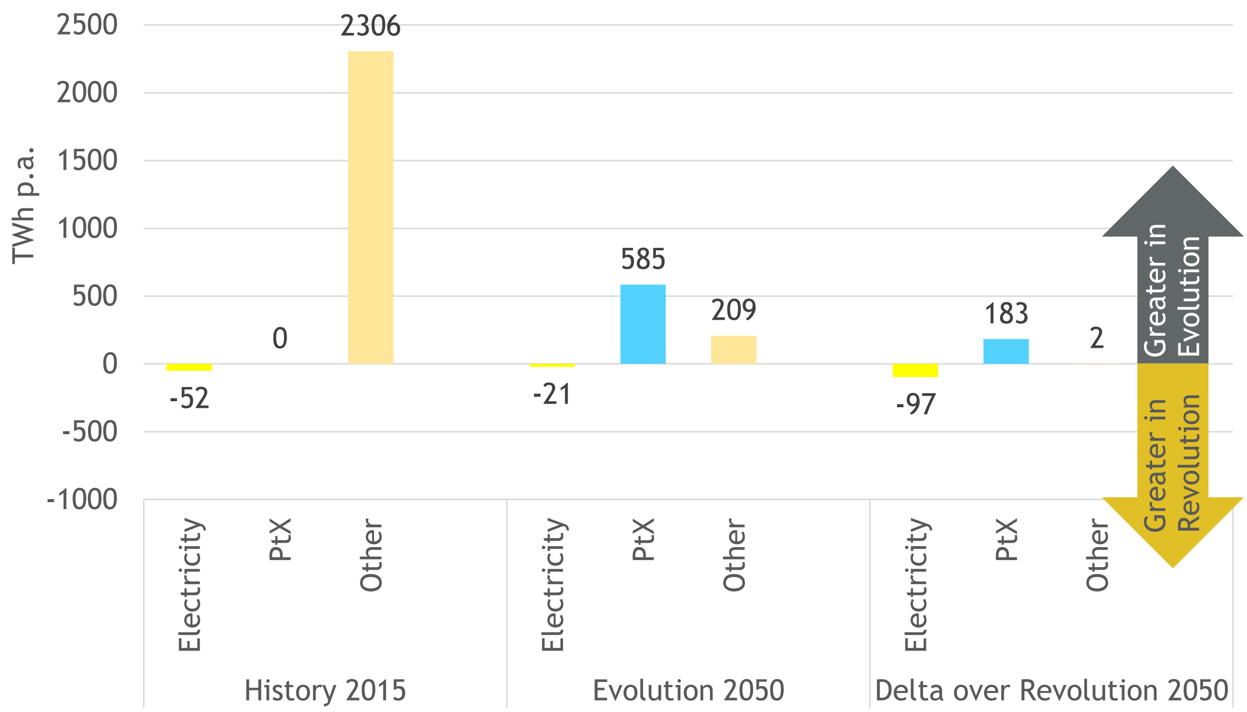

FIGURE 38: ENERGY IMPORTS[14] TO GERMANY IN 2015 AND 2050 IN THE EVOLUTION SCENARIO

3.6 Costs

3.6.1 Direct annual expenditure on energy conversion and energy consumption

2017 TO 2030

In the Evolution scenario, annual expenditure on energy conversion and energy consumption rises by €14 billion to €113 billion in 2030. The annual cost rise is therefore €3.9 billion higher than in the Revolution scenario. At a figure of €3.3 billion, the greatest additional costs are for fuels. This is due to the greater demand for conventional fuels by the Buildings and Industry consumer sectors compared with the Revolution scenario. Moreover, operating and maintenance costs are slightly higher (+ €1.2 billion) in the Evolution scenario than in the Revolution scenario. The cost differences based on data from the BDEW heating cost comparison (BDEW (2016) and BDEW (2017)), which assume slightly lower maintenance costs for heat pumps than for gas heating systems. Conversely, there is less dependence upon electricity imports in the Evolution scenario. As a result, expenditure on electricity imports is €0.6 billion lower in the Evolution scenario. In both scenarios, the same Power-to-X import is required in 2030, so there is no difference in these costs.

[14] Electricity and Power-to-X in final energy, others in primary energy. The historical data is based on the evaluation tables for Germany's energy balance from company energy balances and have been adjusted to exclude non-energy-related consumption.

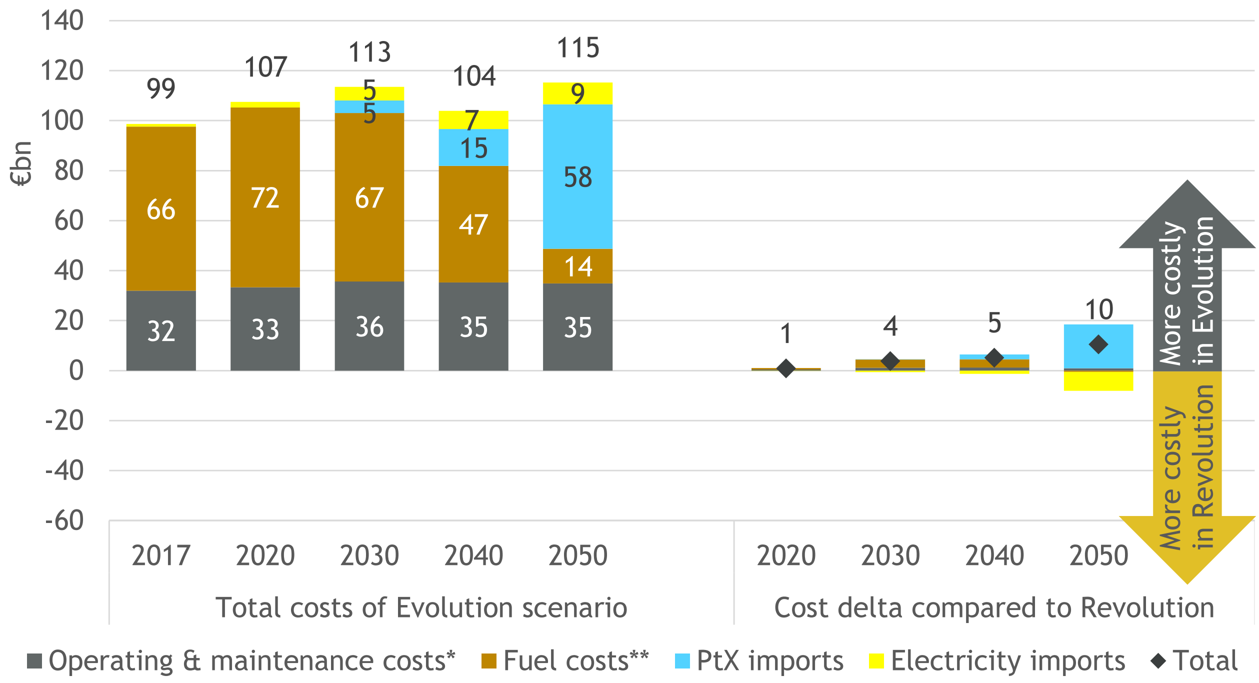

FIGURE 39: DIRECT ANNUAL EXPENDITURE ON ENERGY CONVERSION AND CONSUMPTION IN THE EVOLUTION SCENARIO AND COMPARISON WITH REVOLUTION SCENARIO[15]

2030 TO 2050

In the Evolution scenario, as in the Revolution scenario, the structure of direct annual expenditure on energy conversion and energy consumption changes fundamentally between 2030 and 2050. The level of costs in 2050 only differs slightly from 2030, being €1.7 billion higher. Compared with the Revolution scenario, additional costs of €5.2 billion arise in 2040 and €10.5 billion in 2050. The cost differences between the Evolution and Revolution scenarios are more or less the same in 2040 as they are in 2030. There is a much greater difference between the scenarios in 2050. The strict CO_2 targets combined with a higher proportion of conventional energy consumption than in the Revolution scenario, namely gas in the Buildings and Industry sectors, lead to a much higher demand for synthetic fuels. The extra requirement is covered by extra production in Germany and also by extra imports. The additional annual costs for Power-to-X imports relative to the Revolution scenario amount to €17.6 billion. This huge cost difference is driven by assumptions about the costs of Power-to-X. If costs for Power-to-X develop more advantageously, the additional costs would be much lower. The additional costs in the "Technology push - Gas" sub-scenario are outlined in Chapter 4.2.2. These additional costs are offset by savings on electricity imports relative to the Revolution scenario. As a result of lower electricity demand, only half as much electricity is imported than in the Revolution scenario. This gives rise to savings of €7.5 billion relative to the Revolution scenario. In 2050, there is hardly any difference between the scenarios in terms of operating and maintenance costs and fuel costs (excluding electricity and Power-to-X imports). For example, in 2050, operating and maintenance costs are €35 billion

[15] * Operating and maintenance costs for power stations, Power-to-X plants, renewable plants, building insulation and heating systems.
** Costs for conventional and biogenic fuels.

and hence €0.9 billion higher than in the Revolution scenario. This cost disadvantage is down to higher maintenance costs for gas heating systems. Costs for fossil and biogenic fuels are €0.5 billion in the Evolution scenario and therefore slightly below the costs in the Revolution scenario. The fact that costs are practically identical is because, in the Evolution scenario, the extra demand for conventional fuels is covered entirely by synthetic energy carriers. The cost difference is a result of slight differences in the composition of the fossil and biogenic fuels procured.

3.6.2 Investment costs

2017 TO 2030

In the Evolution scenario, investment in the Building sector is not regulated by any political requirements, so that investment decisions can be taken without bias towards any particular technology and only with a view to achieving climate targets at minimal cost. Investment costs are shown in Figure 40. This means that expenditure in the Building sector will increase from nearly €5.9 billion in 2017 to €9.1 billion in 2030, in line with falling CO_2 emissions. However, these costs are only half those in the Revolution scenario, in which a renovation rate of 2% and the ambitious expansion of heat pumps are prescribed. Overall, annual savings on investments in the Evolution scenario are between €7.9 billion and €11.1 billion. This means that, compared with the Revolution scenario, the saving on investments in the years up until 2030 in the Evolution scenario is more than twice the amount of additional costs for energy conversion and consumption.

There is no difference in the political requirements in the Energy industry, so that investments are largely driven by the CO_2 target and/or by electricity demand (output and capacity). In the Evolution scenario, annual investment costs increase from €8.2 billion to €13.5 billion. Due to the slightly lower electricity demand and peak load in the Evolution scenario, annual investments in the Energy industry in the years up until 2030 are up to €0.9 billion lower than in the Revolution scenario. Specifically, far fewer new gas-fired power stations are built during this period.

2030 TO 2050

Against the background of increasingly strict CO_2 requirements, investment costs continue to increase both in the Building sector and the Energy industry. Overall, annual investments increase by €9 billion, from €22.7 billion to €31.7 billion. €3.8 billion of additional costs arise in the Building sector. This cost increase is predominantly due to the increased replacement of oil and gas-fired heating systems by heat pumps in renovated buildings. Annual investment costs in the Energy industry increase from €13.5 billion to €18.2 billion. As in the Revolution scenario, this increase is due to an increasing rate of expansion of renewable plants, the pressure to invest in more expensive technologies because limits have been reached in terms of potential available area, and the necessary construction of new gas-fired power stations.
Despite the rise in costs in both sectors, investment costs are between €8.8 billion and €9.3 billion lower than in the Revolution scenario. Specifically, savings of between €7.9 billion and €7.4 billion are achieved in the Building sector and savings of around €1.5 billion in the Energy industry

relative to investments in the Revolution scenario. In the Building sector, these savings are due to the much lower level of investment in insulation and heat pumps. The savings in the Energy industry are due to a much smaller increase in electricity demand and peak load in the Evolution scenario than in the Revolution scenario. This means that there can be a huge reduction in the construction of new gas-fired power station and a slight reduction in renewables.

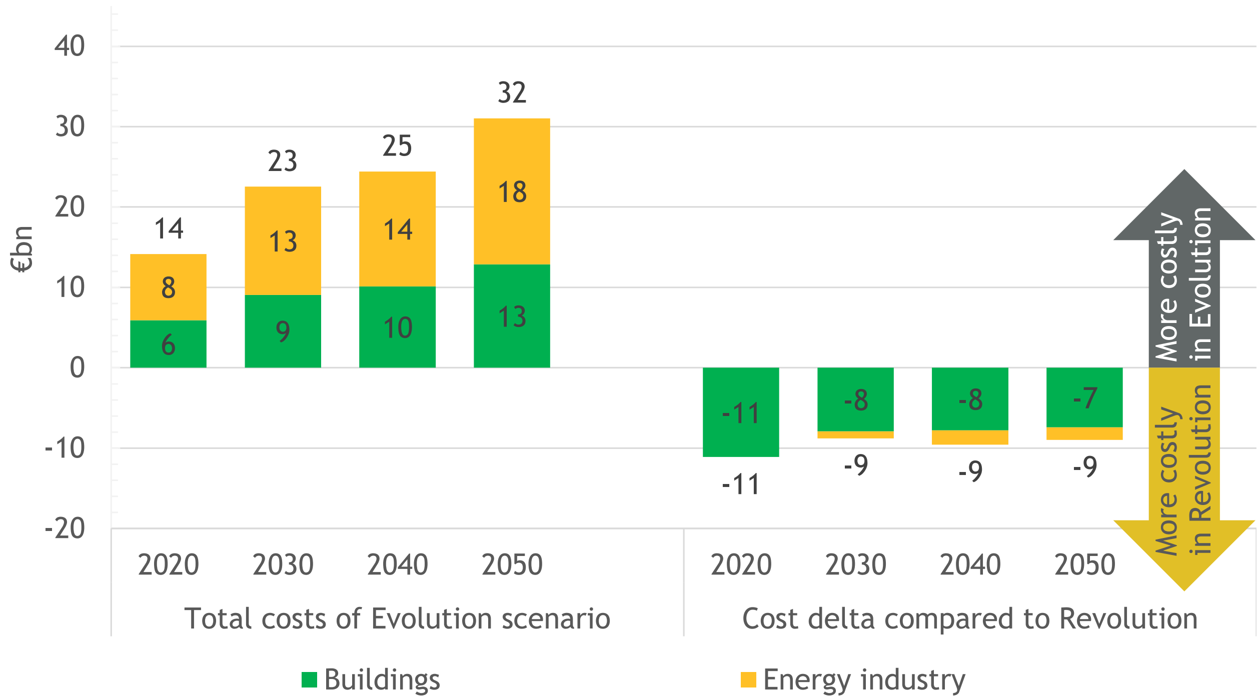

FIGURE 40: ANNUAL INVESTMENTS IN THE BUILDINGS AND ENERGY INDUSTRY SECTORS IN THE EVOLUTION SCENARIO AND COMPARISON WITH THE REVOLUTION SCENARIO

3.6.3 Network costs

2017 TO 2030

Figure 41 illustrates costs for electricity, gas and heat networks over the period. Annual network costs increase by €5.6 billion between 2017 and 2030, namely from €31.2 billion to €36.8 billion. As in the Revolution scenario, this cost rise is predominantly due to expansion of the electricity network, which gives rise to additional annual costs of €5.2 billion up until 2030. However, compared with the Revolution scenario, there is an annual cost saving of €1.1 billion. Savings on expansion of the distribution networks (-€1.0 billion relative to Revolution scenario) are predominantly due to a lower peak load. One of the reasons for this is the lower electricity demand in the Building sector, due to the use of heat pumps. There is hardly any difference between the scenarios in terms of the cost increase for expansion of the transmission network (-€0.1 billion relative to Revolution scenario), since there is a similarly intensive expansion of renewables. In addition to this, gas infrastructure costs increase slightly up until 2030 (+ €0.5 billion). Since the majority of investments have already been determined by NEP Gas 2016, and are explained by the changeover from L gas to H gas, there is hardly any difference in network costs. However, there are additional costs of €0.3 billion compared with the Revolution scenario, due to the 15% greater demand in the distribution network. In the Evolution scenario, the demand for local and district heat increases by approximately 10% (+12 TWh) by 2030. Since these increases in demand are primarily due to the expansion and densification of existing heat networks, infrastructure costs for heat networks only increase by €0.1 billion by 2030. This gives rise to additional costs of €0.2 billion relative to the Revolution scenario. Aggregated over all the networks considered, annual network costs in the Evolution scenario are €0.6 billion lower than in the Revolution scenario.

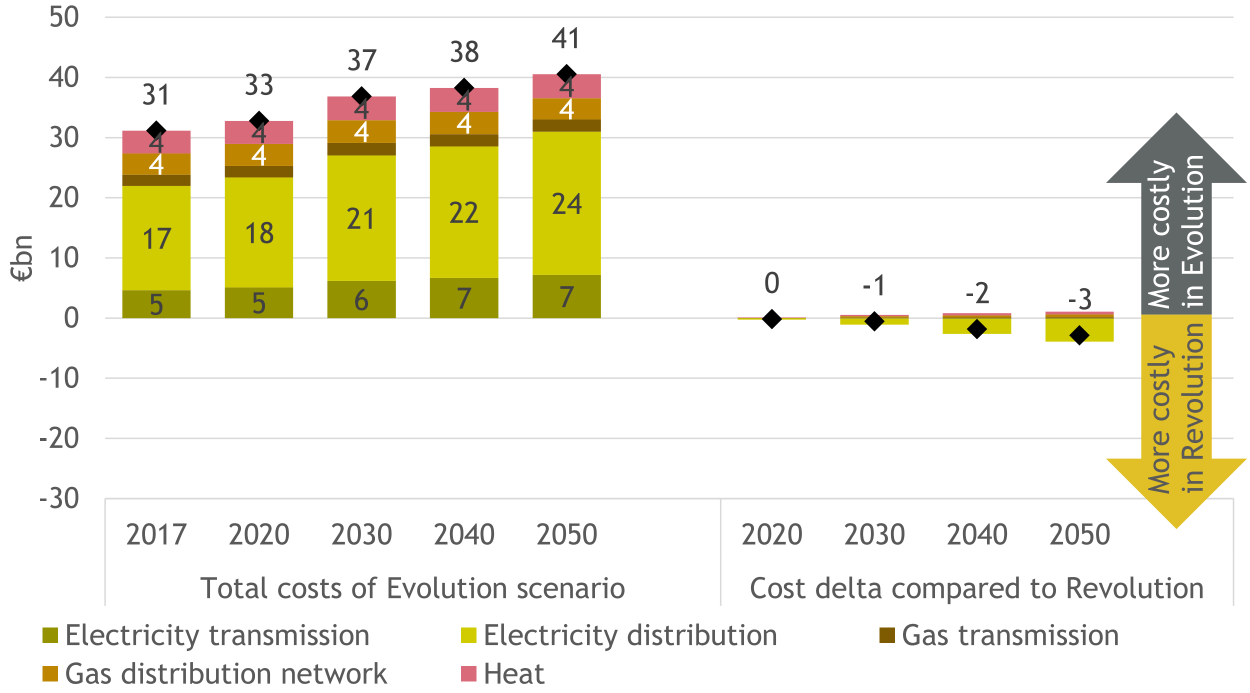

FIGURE 41: ANNUAL NETWORK COSTS OF POWER, GAS AND HEAT NETWORKS IN THE EVOLUTION SCENARIO AND COMPARISON WITH REVOLUTION SCENARIO

2030 TO 2050

Between 2030 and 2050, annual network costs increase by a further €3.8 billion to €40.5 billion. Additional costs of €3.9 billion are due to further expansion of the electricity network. As in the Revolution scenario, this is necessary due to the further expansion of renewables and the continued spread of electro mobility. However, since demand is lower in the Buildings and Industry sectors, less expansion is required, particularly of the distribution network. This increases the saving over the Revolution scenario from €1.1 billion in 2030 to €3.9 billion in 2050. Network costs for gas infrastructure fall from €5.9 billion in 2030 to €5.6 billion in 2050. This is because the level of investment declines significantly over this period. On the other hand, the difference relative to the Revolution scenario increases from €0.3 billion in 2030 to €0.6 billion in 2050. This is partly due to higher costs for fuel gas and other variable operating costs and also to slightly higher investment. However, practically no dismantling of the distribution network (€0.2 billion) takes place in the Evolution scenario. This is because there is only a slight drop in household demand for gas (from 229 TWh in 2015 to 208 TWh in 2050), while, in the Revolution scenario, it is down to 55 TWh in 2050. This equates to a saving of €10.4 billion relative to the Revolution scenario. Due to further expansion of heat infrastructure, there is a much smaller increase in costs for heat infrastructure from €3.9 billion in 2030 to €4.0 billion in 2050. Total annual savings for network-related energy infrastructure increase in the Evolution scenario from €0.6 billion in 2030 to €2.9 billion in 2050. In addition to this, €10.2 billion of dismantling costs are saved.

3.6.4 Comparison of total costs of the Revolution and Evolution scenario

Based on the results of Chapter 2.6 and Sections 3.6.1 to 3.6.3, the following section compares the cumulative costs of the Revolution and Evolution scenarios. In order to do this, the investment costs of both scenarios are converted into capital costs. This is based on assumptions regarding useful service life and interest rates. The resulting total annual costs are then cumulated for the two periods under consideration.

2017 TO 2030

Figure 42 shows the cost differences between the Evolution and Revolution scenarios. For the period between 2017 and 2030 there are cumulative savings of €23.6 billion in the non-technology-biased Evolution scenario compared with the Revolution scenario. In the latter scenario, CO_2 savings are implemented by mandatory electrification in the Buildings and Industry sectors. This corresponds to an annual saving of €715 million. The additional costs of the Evolution scenario resulting from the comparatively small decline in demand for fossil and biogenic fuels (+€28.3 billion), higher operating and maintenance costs (+€10.4 billion) and minimally higher Power-to-X import costs (+€0.2 billion) are more than offset by savings in the other cost categories. Since far fewer renovations are done and heat pumps installed, capital costs of €51.5 billion can be saved in the period between 2017 and 2030. Moreover, the small extent of electrification in the energy consumer sectors leads to cumulative savings on network costs of €4.8 billion between 2017 and 2030. Furthermore, during the same period, cumulative costs for electricity imports are €6.3 billion lower than in the Revolution scenario.

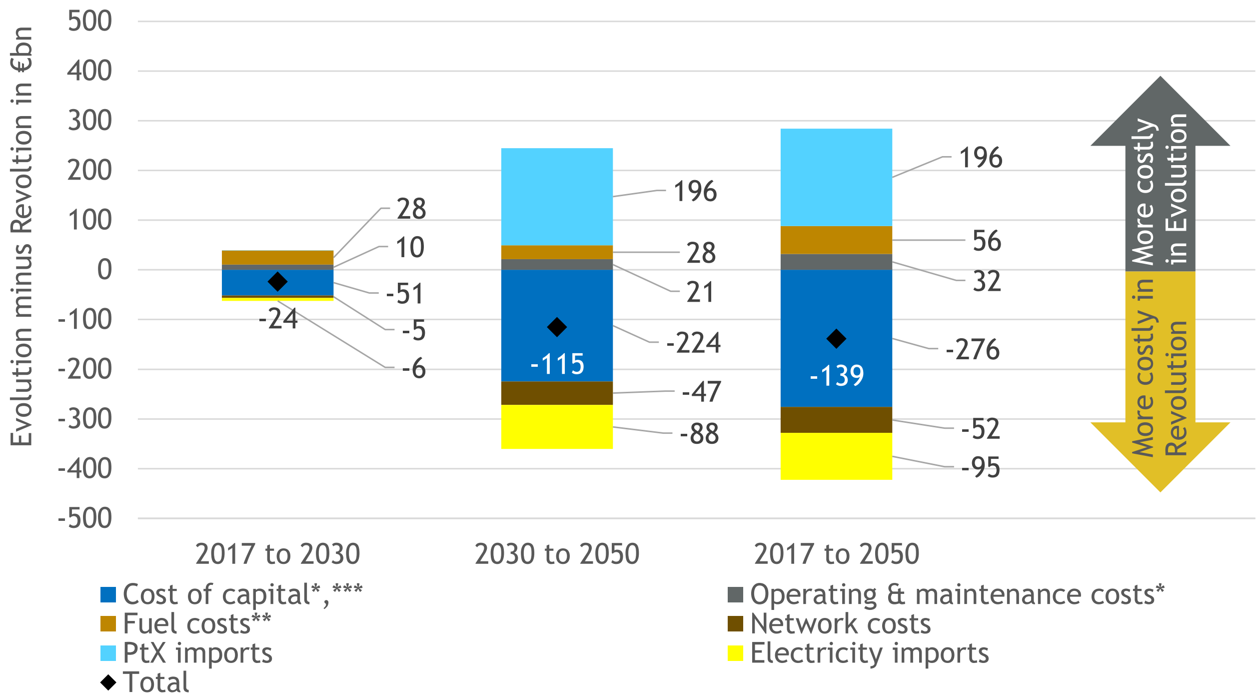

FIGURE 42: CUMULATIVE COST DIFFERENCES BETWEEN THE EVOLUTION AND REVOLUTION SCENARIOS[16]

2030 TO 2050

The period between 2030 and 2050 sees an increase in the cost differences for the different types of cost in the two scenarios. Moreover, the cumulative savings of the Evolution scenario as against the Revolution scenario increase significantly to €115.1 billion. In annual terms, the savings of the Evolution scenario increase eightfold relative to the period from 2017 to 2030, increasing from €715 million to €5.8 billion. This development results from the development of the different cost categories described below:

Cumulative additional costs of €195.6 billion arise in the Evolution scenario, due to the much greater quantities of synthetic fuels imported. In addition to this, there are higher costs for fossil and biogenic fuel in this period (+€28.0 billion), since these are more heavily used in the Evolution scenario than in the Revolution scenario, particularly up until 2040. There are also higher total operating and maintenance costs (+€21.3 billion), due to the higher operating and maintenance costs of gas heating systems. However, savings in the other cost categories far outweigh the additional costs mentioned above. As in the period between 2017 and 2030, the largest savings of the Evolution scenario are the result of much lower capital costs in the Building sector and the Energy industry. Specifically, these savings amount to €224.4 billion and result from saving on insulation and heating installation, as well as less investment in renewable energies and gas-fired power stations. Further cumulative savings of €47.7 billion are due to lower network costs. Much less investment in electricity networks is primarily responsible for this. The savings resulting from these two cost components alone exceed the total additional costs of the scenario (for Power-to-

[16] * Capital and operating and maintenance costs for power stations, Power-to-X plants, renewable plants, building insulation and heating systems.
** Costs for conventional and biogenic fuels. *** Capital costs resulting from annuating investment costs.

X imports, fuels and maintenance and operation) by more than €25 billion. Savings of €88.3 billion are also made as a result of the much lower electricity imports between 2030 and 2050.

CUMULATIVE ANALYSIS OF THE PERIOD 2017 TO 2050

Between 2017 and 2050 there are cumulative savings of €138.8 billion in the non-technology-biased Evolution scenario. This corresponds to an annual saving of €4.2 billion. These cost savings are due to the fact that, in the sectors considered here, namely Energy industry, Buildings, Industry (excluding process emissions) and Transport, the 95% CO_2 target is better achieved by increased use of synthetic fuels than by electrification of the Buildings and Industry sectors. Figure 43 is a waterfall diagram showing the cost differences by type of cost. It can be seen that, in the Evolution scenario, savings are notably the result of lower capital costs. Moreover, the additional costs of the Evolution scenario due to higher Power-to-X imports are offset by significant savings on electricity imports.

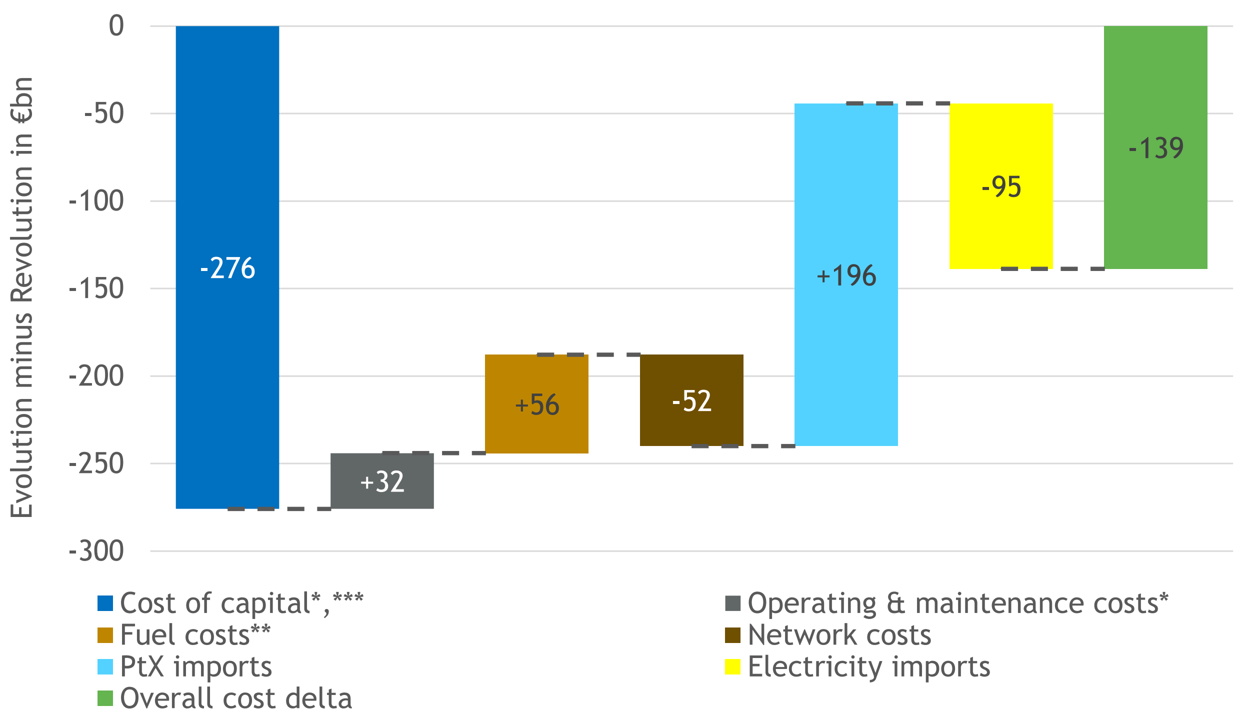

FIGURE 43: CUMULATIVE COST DIFFERENCES BETWEEN THE EVOLUTION AND REVOLUTION SCENARIOS FROM 2017 TO 2050[17]

[17] * Capital and operating and maintenance costs for power stations, Power-to-X plants, renewable plants, building insulation and heating systems.
** Costs for conventional and biogenic fuels. *** Capital costs resulting from annuating investment costs.

3.7 Repercussions on gas distribution and heat networks

3.7.1 Gas distribution networks

2017 TO 2030

In the same way as for the Revolution scenario, Figures 44 and 45 show the development of gas demand, gas network costs and network charges in the Evolution scenario. In contrast to the Revolution scenario, gas demand increases by 6.6% between 2017 and 2030 in the Evolution scenario in "Network H" dominated by household customers, to a figure of 1,066 GWh. This is because a large number of oil-fired heating systems are replaced by gas heating in this scenario. In addition to this, due to higher demand in the example network, costs increase more than in the Revolution scenario (from €9.5 million in 2017 to €10.3 million in 2030). As a result of these developments, network charges remain constant, guaranteeing the economic operation of gas networks. Conversely, "Network I" sees an 8.8% drop in demand. This is driven by greater industrial efficiency. However, the drop in demand is only half as great as in the Revolution scenario. In addition to this, costs increase more than in the Revolution scenario, namely to €8.2 million. Overall this results in an increase of 15% in network charges, which is moderate compared with the Revolution scenario. Since the increase is moderate and industrial customers cannot easily change their energy carrier without expensive investment, very few customers will presumably replace gas by another energy carrier. Under these conditions, the economic operation of a network dominated by industrial customers is also guaranteed.

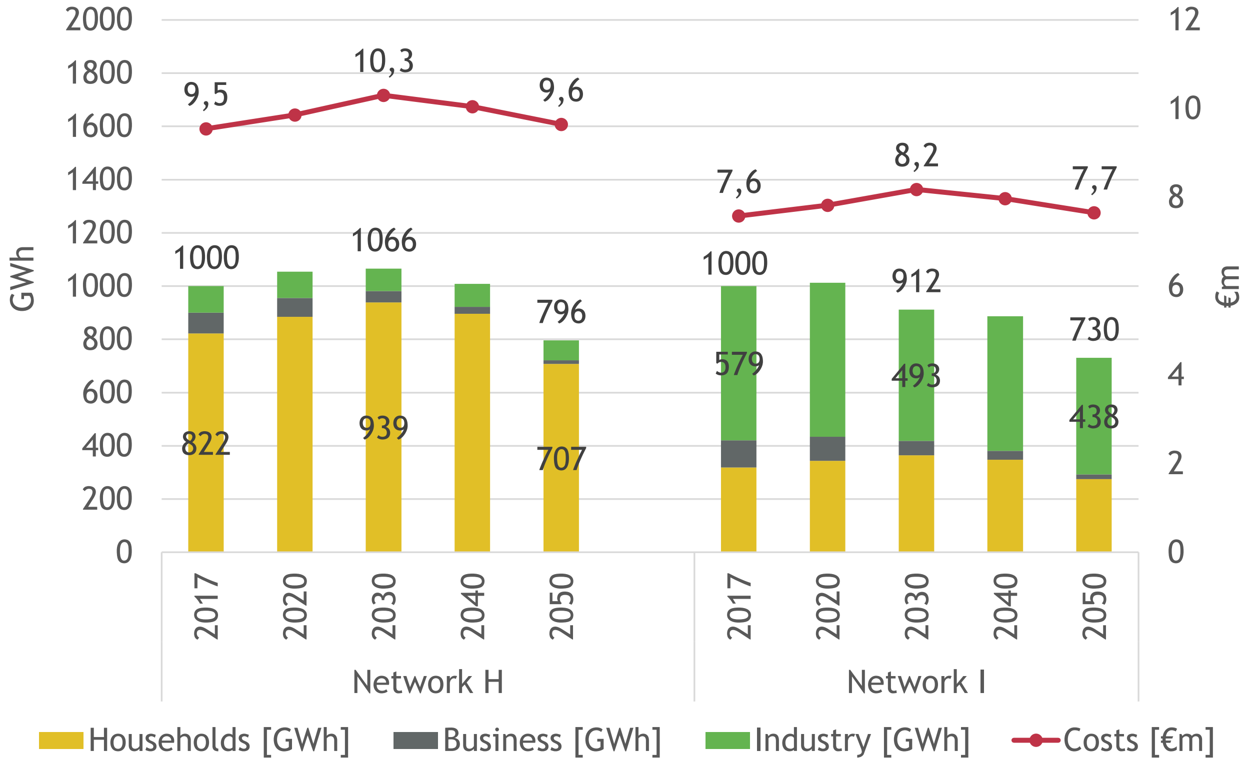

FIGURE 44: DEVELOPMENT OF DEMAND AND COSTS IN THE EXAMPLE NETWORKS IN THE EVOLUTION SCENARIO

2030 TO 2050

In the Evolution scenario, quantities of gas fall between 2030 and 2050 in both networks. In "Network H" they fall by 25% relative to 2030 to 796 GWh and in the "Network I" by 20% to 730 GWh. The decline relative to 2017 is 21% and 27% respectively. Moreover, the costs of both networks are only 1% higher at this point than they are today (2017). This means that cost-covering network charges in the predominantly residential "Network H" are around 25% higher than in 2017 and 2030. Network charges for household customers are barely 1.3 €ct/kWh in 2050. Network charges are much lower than in the Revolution scenario, in which network charges increase so sharply that economic operation of the networks is presumably no longer possible. In 2050, network charges for household customers are 64% or 2.3 €ct/kWh lower in the Evolution scenario than in the Revolution scenario. Because of the moderate increase in network charges, many households are unlikely to swap their gas heating for heat pumps. This analysis is confirmed by DIMENSION+ calculations, in which the network charges for heating systems are endogenous variables. In "Network I" dominated by industrial customers, network charges increase by 20% relative to 2030 and 38% relative to 2017. This increase is much smaller than in the Revolution scenario, in which network charges more than double. While economic operation of the predominantly industrial network is in jeopardy in the Revolution scenario, it is presumably possible in the Evolution scenario.

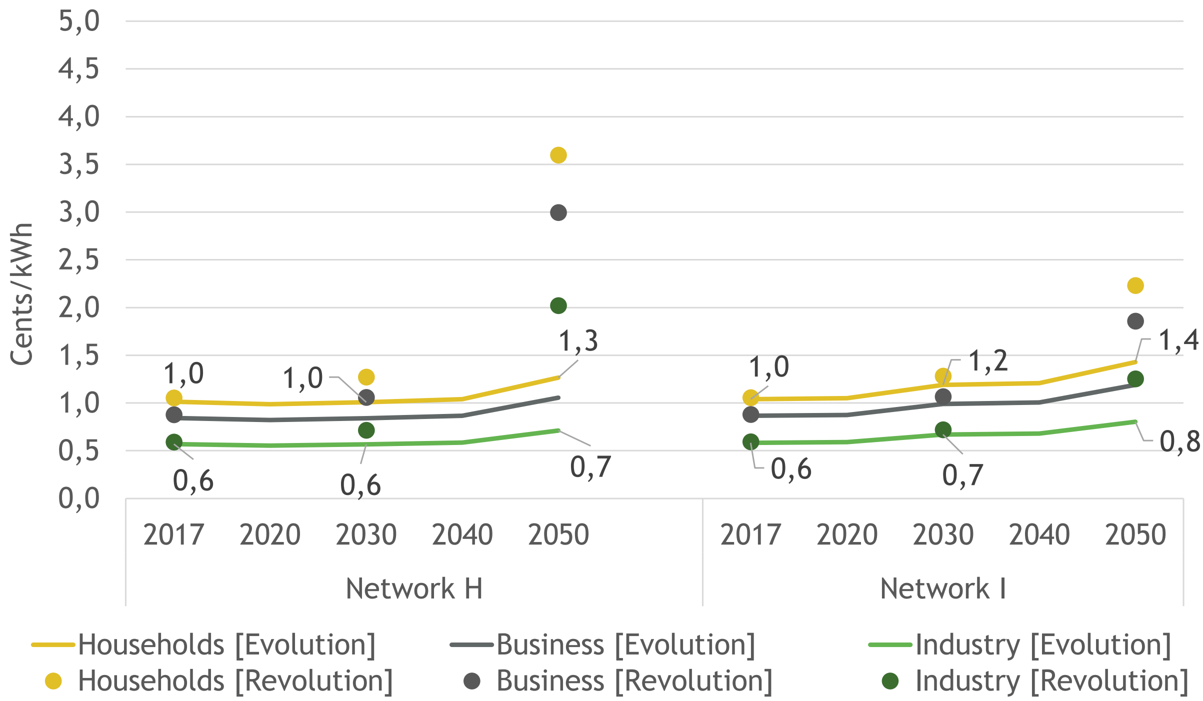

FIGURE 45: DEVELOPMENT OF NETWORK CHARGES IN THE EXAMPLE NETWORKS IN THE EVOLUTION SCENARIO AND COMPARISON WITH THE REVOLUTION SCENARIO

3.7.2 Heat networks

2017 TO 2030

As was done for the Revolution scenario, Figure 46 shows the development of demand, costs and revenue of heat networks in the Evolution scenario. While the demand for district and local heat falls by 21% between 2017 and 2030 in the Revolution scenario, it increases by 14% in the Evolution scenario. If one assumes that prices stay the same, this same difference is reflected in revenue. Since most of the increase in demand is a result of densification of the network, costs only rise minimally. This results in a €0.6 million increase in profits for the operator of the example network, whereas, in the Revolution scenario, profits fall by €0.8 million for the same example network and the same period. In the Evolution scenario, the economic viability of the example network is not endangered, whereas the situation is much more critical for heat network operators in the Revolution scenario.

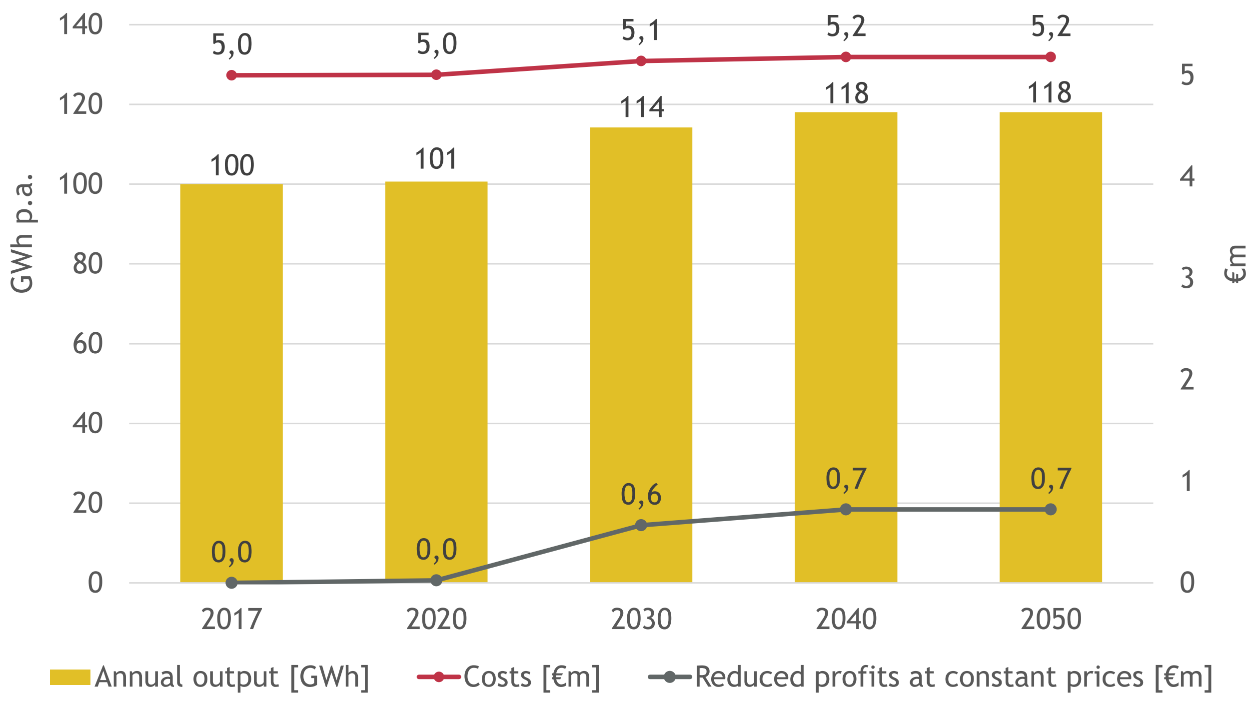

FIGURE 46: DEVELOPMENT OF DEMAND, COSTS AND REVENUES IN EXAMPLE HEAT NETWORKS IN THE EVOLUTION SCENARIO

2030 TO 2050

Demand increases by a further 3% between 2030 and 2050. This corresponds to an increase of 18% relative to 2017. This increase contrasts with the development in the Revolution scenario, in which there is a 50% drop relative to 2017. If prices remain the same, this contrast is mirrored by revenues. Costs are only slightly higher in the Evolution scenario, since the majority of existing costs are fixed costs and increases in demand due to densification of the networks only give rise to a small amount of additional costs. This means that, in the Evolution scenario, there is a slight increase in the network operator's profits (+ €0.1 million relative to 2030 and + €0.7 million relative to 2017), whereas there is a massive drop in the Revolution scenario (- €0.7 million relative to 2030 and - €2 million relative to 2017). While profitable operation of heat networks in 2050 is highly improbable in the Revolution scenario, in the Evolution scenario there is a significant increase in profits by 2050. In addition to this, there is also some leeway for network operators to pass some of the falling costs per kWh on to their customers.

4 ANALYSIS OF UNCERTAIN TECHNOLOGICAL DEVELOPMENT BETWEEN 2030 AND 2050

There are a number of uncertainties during the period up until 2050 (e.g. regarding technological development), which do not permit firm planning of the energy system between now and 2050. For this reason, this study includes a simplified analysis of potential technological uncertainties. In order to do this, the two main scenarios Revolution and Evolution are each subdivided into two sub-scenarios. A schematic representation of the scenarios and sub-scenarios can be found in Figure 47. The previous chapters focused on the details of an average, expected development. Below, this study examines what impact the following developments have upon the results: 1) a technology push in the field of electricity-based technologies (e.g. heat pumps) or 2) a technology push in Power-to-X technologies (e.g. electrolysis). Here it is assumed that the considered technologies experience greater reductions in cost in the period between 2030 and 2050, which is currently difficult to forecast, and so offer an advantage over the other group of technologies.

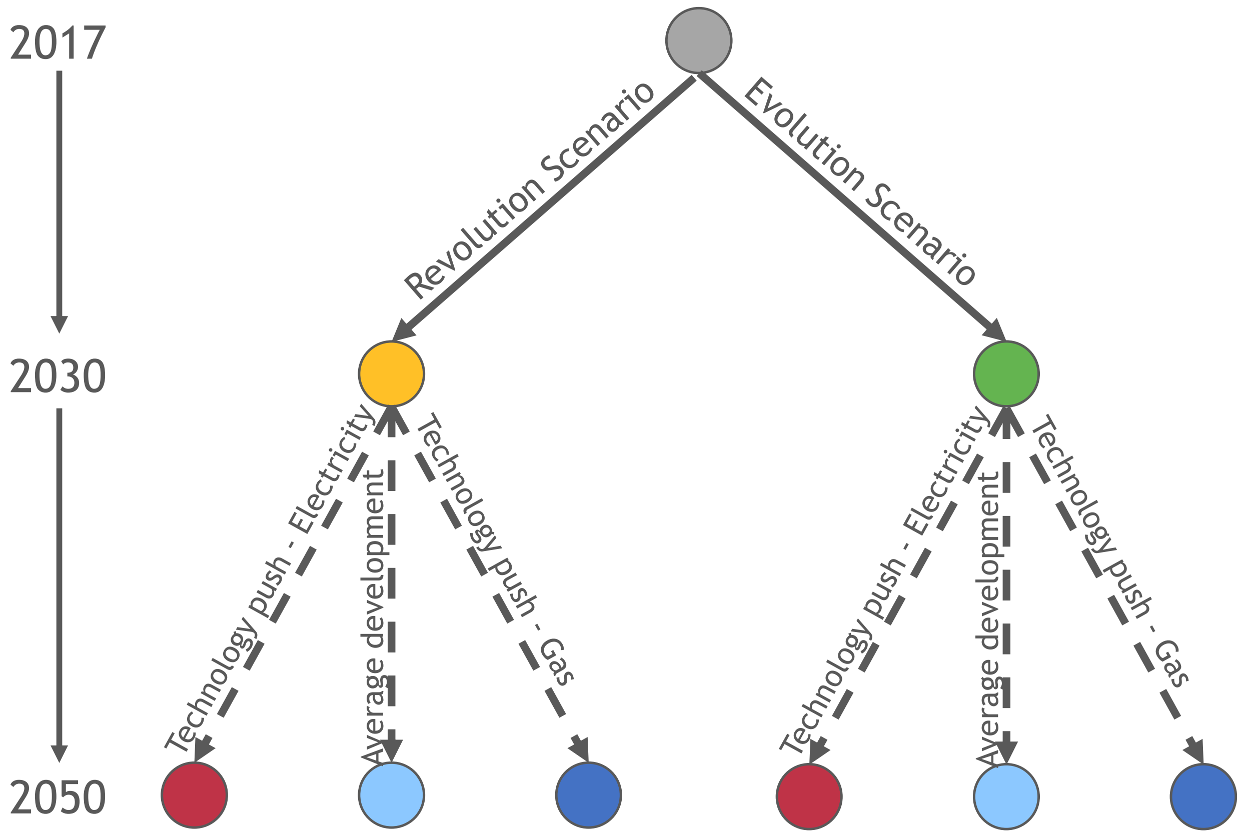

FIGURE 47: SCHEMATIC REPRESENTATION OF THE SCENARIOS

By following this procedure, the uncertainty analysis can answer the question of whether making a decision today in favour of a certain Evolution or Revolution scenario would be economically advantageous or whether a premature decision about a strategy is disadvantageous, i.e. whether the resulting dependencies upon a particular pathway are crucial or obstructive to achieving cost-efficient greenhouse gas reduction. In order to model potential pathway dependencies, the results of the main Evolution and Revolution scenarios are each fixed up until 2030 and then computed with the uncertain developments, i.e. sub-scenarios, for the period 2030 to 2050.

Specifically this means: up until 2030, the sub-scenarios behave like the main Revolution and Evolution scenarios. The decisions that are made up until 2030 can therefore not be revised. This takes account of the fact that decisions made prior to 2030 might then exclude certain options after 2030, because these are then no longer achievable (lock-in effect). This approach therefore serves to examine to what extent the Revolution scenario, for example, can help to avoid early lock-in effects. The aim is also to examine in greater detail to what extent the Evolution scenario with its technologically open design keeps more options in the future, thereby delivering a robust solution under uncertainty of the parameters used.

4.1 Greenhouse gas reduction 2030 to 2050 under uncertainty

The two sub-scenarios of Technology push - Electricity and Technology push - Gas are described below and their specific parameters outlined. In each case the two sub-scenarios are combined with the main Revolution and Evolution scenarios, wherein investment decisions are fixed until 2030.

4.1.1 Technology push - Electricity

In the Technology push - Electricity variant, it is assumed that electricity-based technologies experience a steeper learning curve and downward cost trend than gas-based technologies. This means that heat pumps and heat storages, in particular, are relatively more advantageous than in the development assumed for the main Revolution and Evolution scenarios.

Figure 48 shows the development of investment costs for air heat pumps. In the Technology push - Electricity sub-scenario, investment costs for air heat pumps are 15% lower in the period between 2030 and 2040 than in the average development. Between 2040 and 2050, the cost difference is 20%.

In the same way, it is assumed in this variant that investment costs for other electricity-based technologies such as brine heat pumps or heat storages could also show greater technological advances than gas-based technologies. A detailed description of the differences between the parametric assumptions in the Technology push - Electricity sub-scenarios and main scenarios can be found in Appendix 3, together with the reference sources.

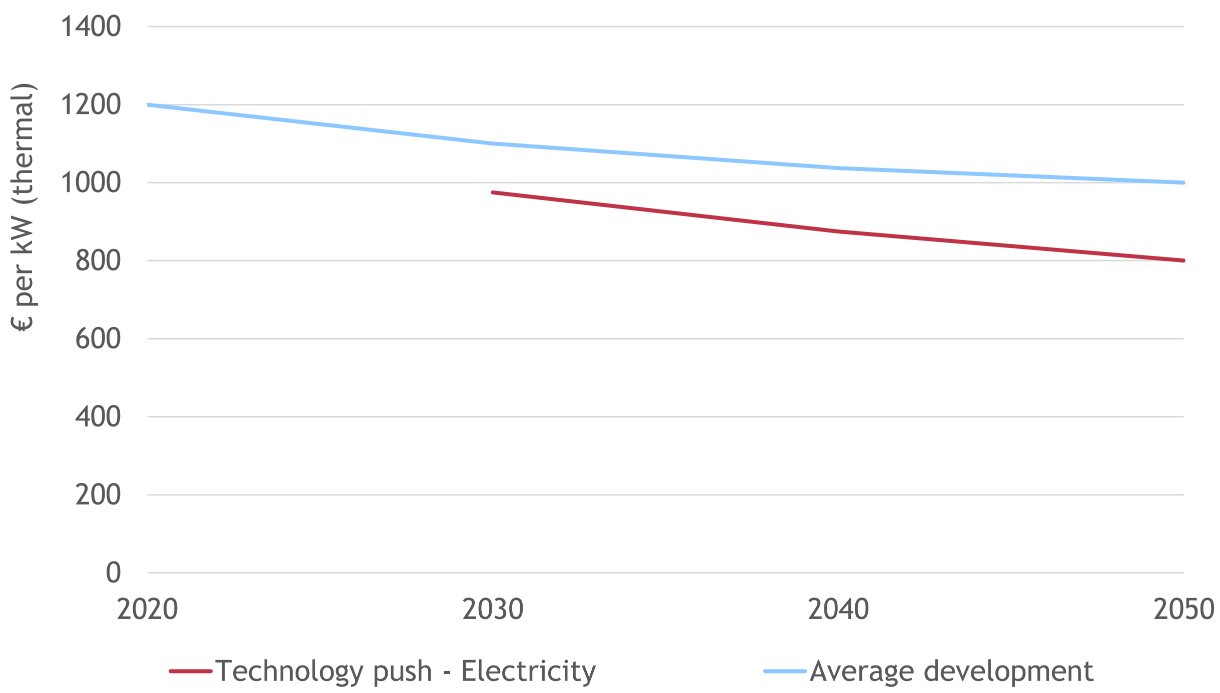

FIGURE 48: DEVELOPMENT OF INVESTMENT COSTS FOR AN AIR HEAT PUMP IN AN AVERAGE DEVELOPMENT AND WITH TECHNOLOGY PUSH - ELECTRICITY

4.1.2 Technology push - Gas

In the Technology push - Gas variant, it is assumed that gas-based technologies experience a steeper learning curve and downward cost trend than those assumed in the main Revolution and Evolution scenarios.

Specifically, it is assumed that investment costs for manufacturing synthetic fuels are lower: in the Technology push - Gas scenario, investment costs for electrolysers are nearly 40% lower than the average development between 2030 and 2040 and then approximately 50% lower between 2040 and 2050. Consequently, costs for importing synthetic fuels from outside the EU also fall and are approximately 25% lower than those in the average development. Figure 49 shows the differences between the average development and the Technology push - Gas scenario for the case of electrolysers. A detailed description of the differences between the parametric assumptions in the Technology push - Gas sub-scenarios and main scenarios can be found in Appendix 3, together with the reference sources.

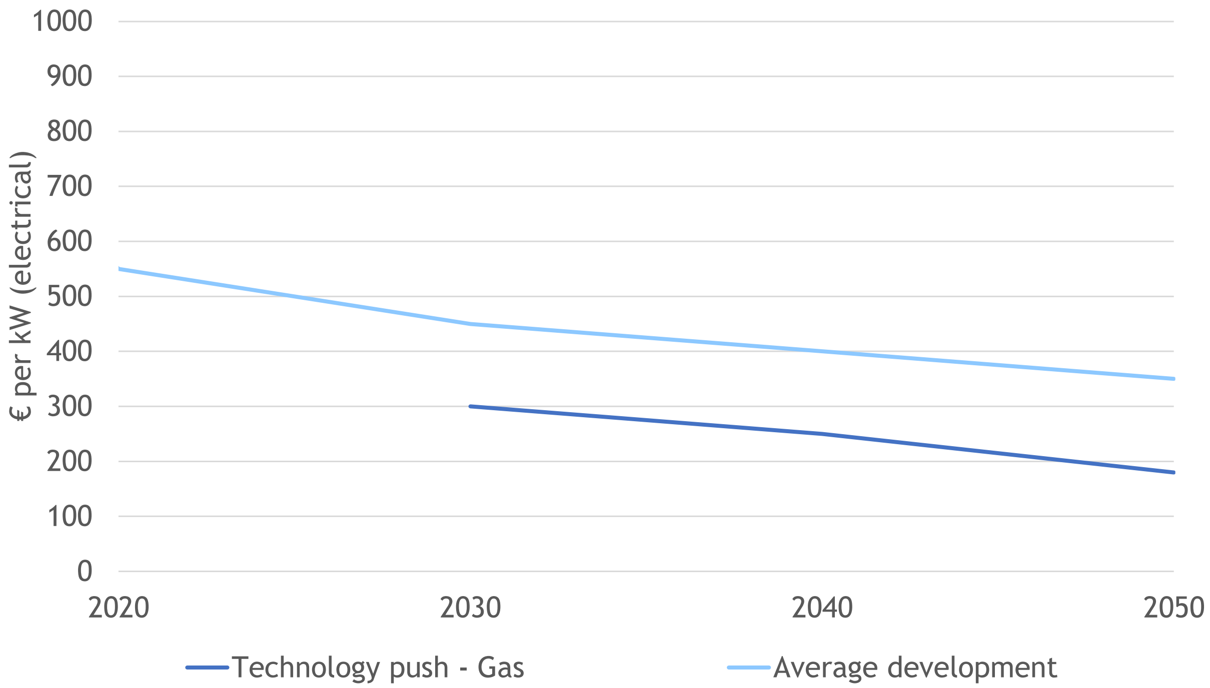

FIGURE 49: DEVELOPMENT OF INVESTMENT COSTS FOR AN ELECTROLYSER IN AN AVERAGE DEVELOPMENT AND WITH TECHNOLOGY PUSH - GAS

4.2 Integrated analysis of variants under uncertainty

4.2.1 Technology push - Electricity

It appears that the technology push of electricity-based technologies in the Evolution scenario leads to a "system change". Although gas heating is the dominant technology for heating buildings up until 2030, the system starts to switch increasingly to electric heat pumps after 2030, since the greater drop in costs now makes these advantageous in a large number of buildings.

Figure 50 shows the number of installed heating technologies in 2050 in the main Revolution and Evolution scenarios. On the right-hand side one can see the two scenarios with Technology push - Electricity. Thus the push in electricity-based technologies in the Evolution scenario leads to the installation of an extra three million heat pumps in place of gas and oil-fired heating systems.

Even though heat pump technologies are only increasingly installed after 2030 in the Evolution scenario, this can still have a great influence upon their inventory by 2050. Assuming that the lifetime of a heating systems is approximately 20 years, the average replacement rate of heating systems of 4% per annum is plausible without more regulatory requirements.
In the Revolution scenario, the inventory of heating technologies cannot react as strongly to the download cost trend, since there is already high market penetration of heat pumps. Nevertheless, approximately 1.3 million more heat pumps are installed in 2050, due to the cost reduction.

Although, by 2050, nearly six million fewer heat pumps are installed in the Evolution scenario than in the Revolution scenario, climate targets are still achieved, due to the use of synthetic fuels, for example.

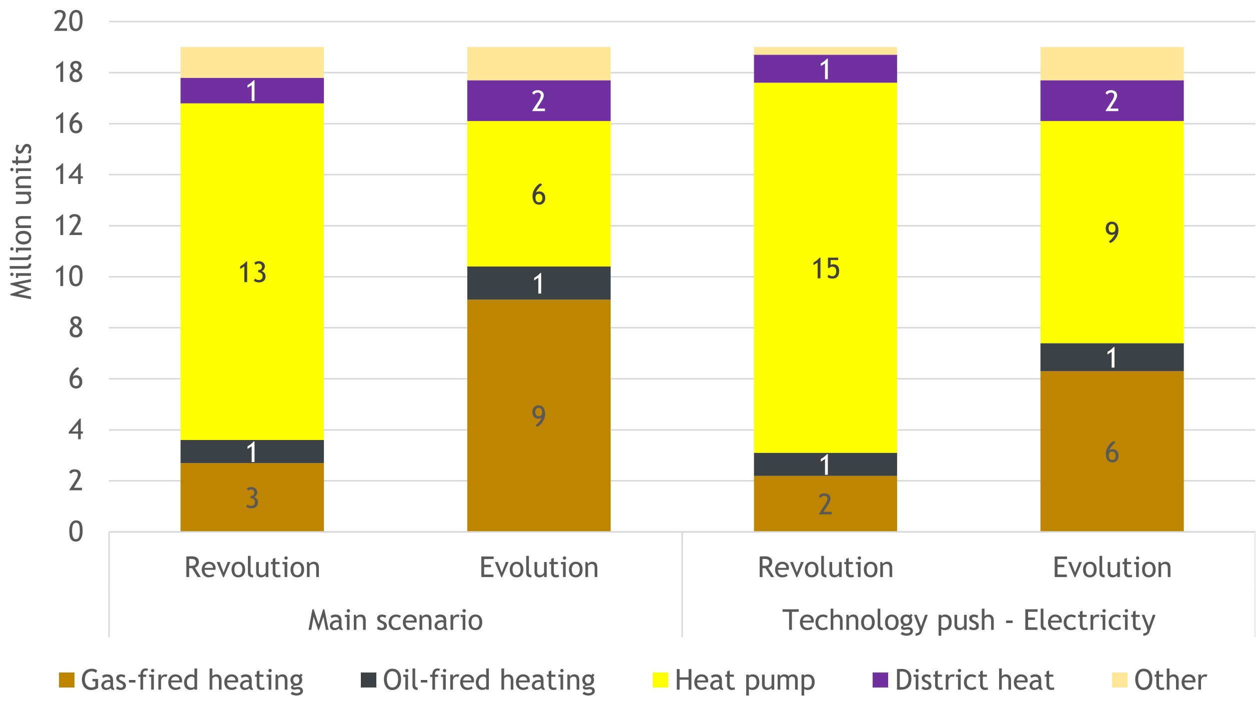

FIGURE 50: INSTALLED HEATING TECHNOLOGIES IN THE YEAR 2050 IN THE MAIN REVOLUTION AND EVOLUTION SCENARIOS AND WITH TECHNOLOGY PUSH - ELECTRICITY

Apart from there being more installed heat pumps, lower investment costs for electricity-based technologies also have an impact on the use of synthetic fuels. Figure 51 shows the use of synthetic fuels in the year 2050 by sector. In both scenarios, the demand for synthetic fuels is approximately 5% lower with Technology push - Electricity than in the main scenario. It can be seen in the Evolution scenario that quantities decline in the Transport and Energy industry sectors compared to the main scenario.

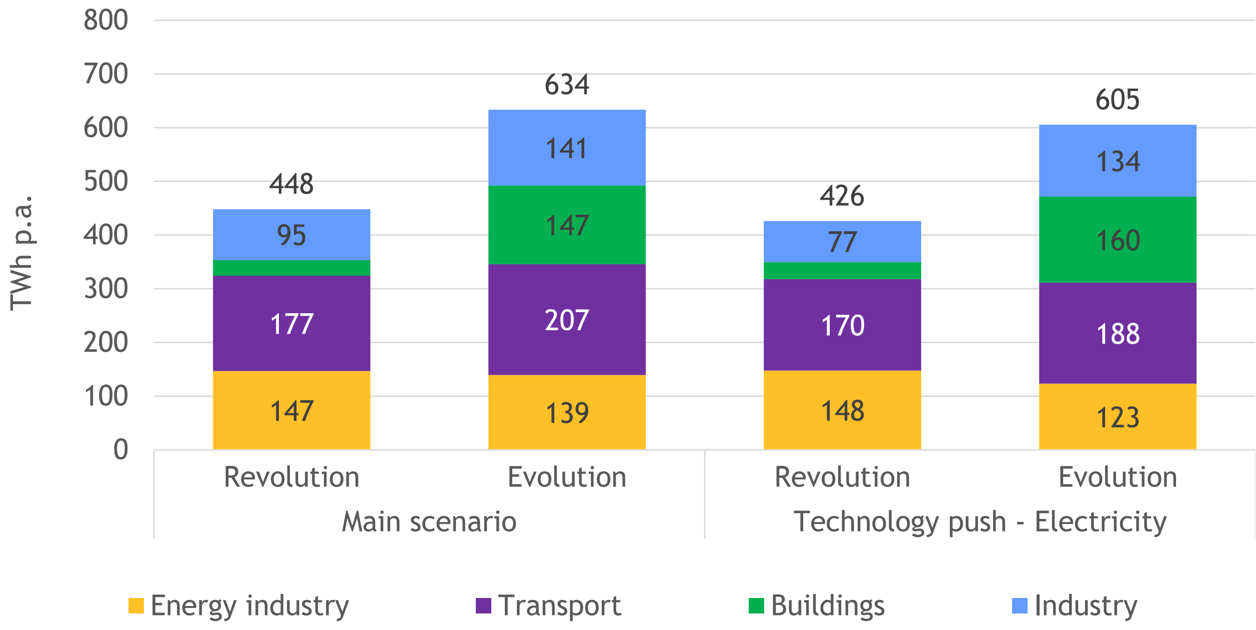

FIGURE 51: USE OF SYNTHETIC FUELS IN THE YEAR 2050 BY SECTOR IN THE MAIN REVOLUTION AND EVOLUTION SCENARIOS AND WITH TECHNOLOGY PUSH - ELECTRICITY

Since investment costs for electricity-based technologies are lower in both the Revolution and Evolution scenarios, total costs also fall in both cases. Figure 52 shows the cost difference between the Evolution and Revolution scenarios. By 2030, the Evolution scenario is approximately €24 billion cheaper than the Revolution scenario. During the period between 2030 and 2050, the Evolution scenario saves a further €115 billion. If the Technology push - Electricity occurs, this cost advantage drops to €106 billion between 2030 and 2050, since even in the non-technology-specific scenario there is increased usage of electric heating applications, particularly in the endogenously modelled Buildings heating sector. This reduces the cost difference between the Revolution and Evolution scenarios, particularly in the area of capital and network costs.

Much greater cost reductions would therefore still be required in the field of electricity-based technologies to make the Revolution scenario more favourable than the Evolution scenario. The Evolution scenario also allows a late change-over to electricity-based technologies, should these become advantageous. However, at the same time, the Evolution pathway saves costs up until 2030.

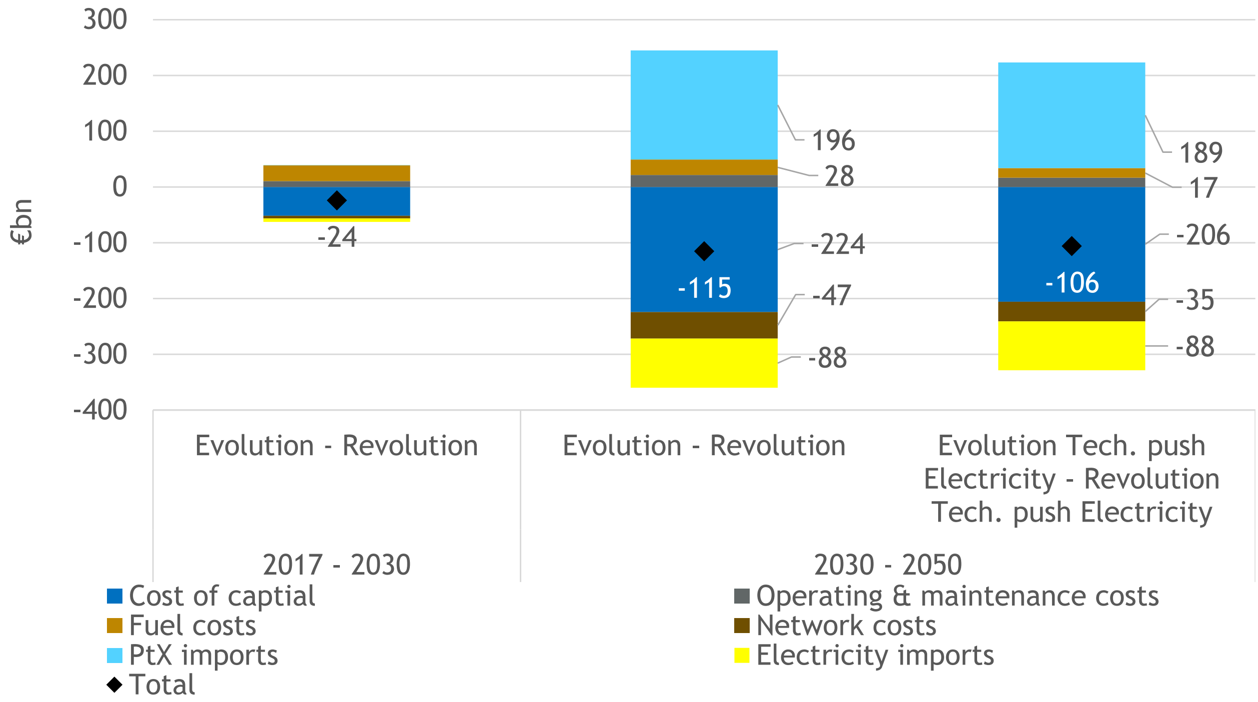

FIGURE 52: CUMULATIVE TOTAL COST DIFFERENCE OF THE MAIN SCENARIOS COMPARED WITH TECHNOLOGY PUSH - ELECTRICITY

4.2.2 Technology push - Gas

In the event of a technological push in gas-based technologies and, in particular, technologies for producing synthetic fuels, the Evolution scenario is able to take full advantage of the situation. Although the lower costs of Power-to-X technologies resulting from the technology push are also beneficial in the Revolution scenario, the advantage is smaller, since heat production, particularly in residential buildings, is strictly tied to electric heating applications.

Figure 53 shows the heating technologies installed in the main scenarios and with Technology push - Gas in the year 2050. It appears that, in the Evolution scenario with Technology push - Gas, no electricity-based heating technologies are used in 2050 but instead gas and oil-based technologies dominate the market. This scenario nonetheless achieves the climate targets, since gas and oil-fired heating systems are operated entirely with synthetic, climate-neutral fuels. A striking difference to the Evolution scenario with average development is that, in this case, gas and oil-fired heating systems are installed in 2050 instead of approximately six million heat pumps. In accordance with its definition, the Evolution scenario permits precisely this reaction to late signals, such as the cost of synthetic fuels being lower than currently expected.

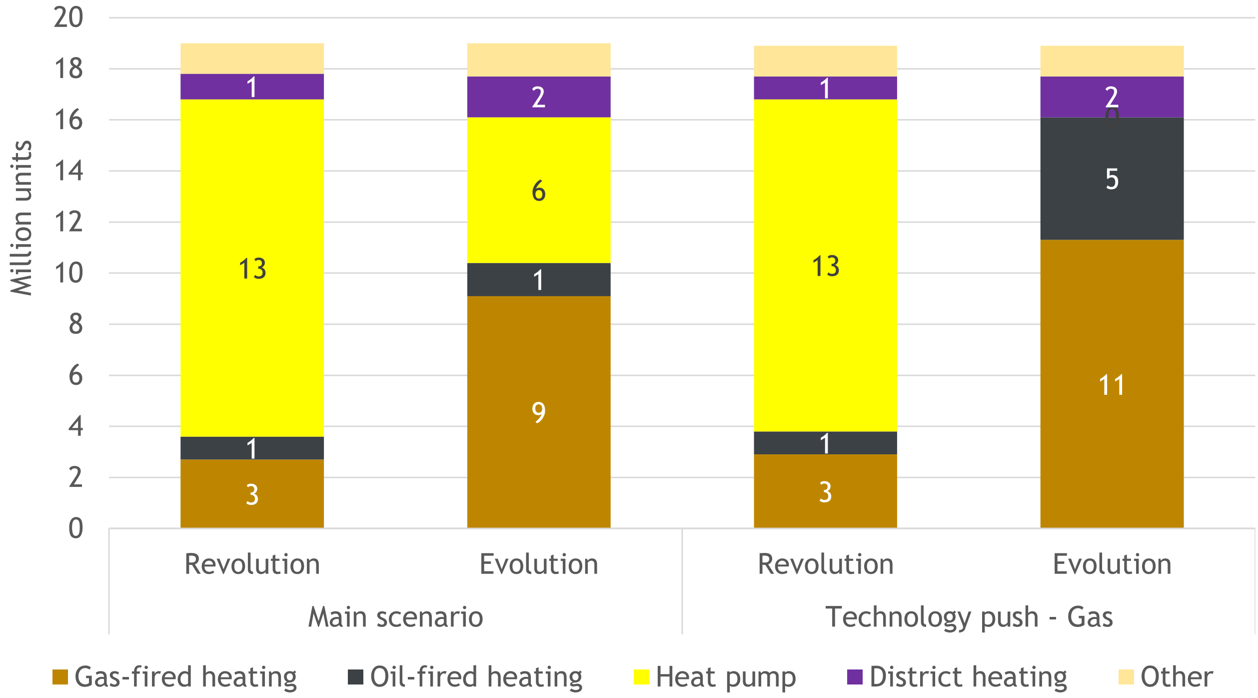

FIGURE 53: INSTALLED HEATING TECHNOLOGIES IN THE YEAR 2050 IN THE MAIN REVOLUTION AND EVOLUTION SCENARIOS AND WITH TECHNOLOGY PUSH - GAS

The use of Power-to-X fuels increases in both scenarios, if the Technology push - Gas occurs. Figure 54 shows the usage of synthetic fuels in the different sectors. In the Revolution scenario, aggregated usage of Power-to-X increases by 122 TWh in 2050, if the Technology push - Gas occurs. In the Evolution scenario, on the other hand, this rise is 138 TWh, even though significantly more synthetic fuels are already used in this scenario.

Due to the technologically permissive and cross-sector optimisation in the Evolution scenario, it is possible for even more comparatively inexpensive Power-to-X to be used in many consumer sectors and climate targets to be met. Different investment decisions are taken for building-heating, in particular.

In the Revolution scenario, relatively inexpensive synthetic fuels are used for reconversion in 2050, assuming Technology push - Gas, especially in the Energy industry. The extent to which this is worthwhile, as compared with direct usage in the final energy consumer sectors, largely depends on the efficiencies that can be achieved in gas-fired power stations.
Even in the Technology push - Gas sub-scenario, the total costs of both scenarios are lower than in the average development of the main scenarios. This is attributable to the lower cost assumptions.

Also, the cost difference between the Evolution and Revolution scenarios increases to a cumulative €192 billion over the entire period from 2017 to 2050. Because of mandatory electrification in the heating market in the Revolution scenario, the Revolution scenario cannot participate in the falling costs of synthetic fuels to the same extent. However, in the event of costs for synthetic fuels being lower, in the technologically permissive Evolution scenario, the optimisation model can also adapt the application technologies in the final energy consumer sectors.

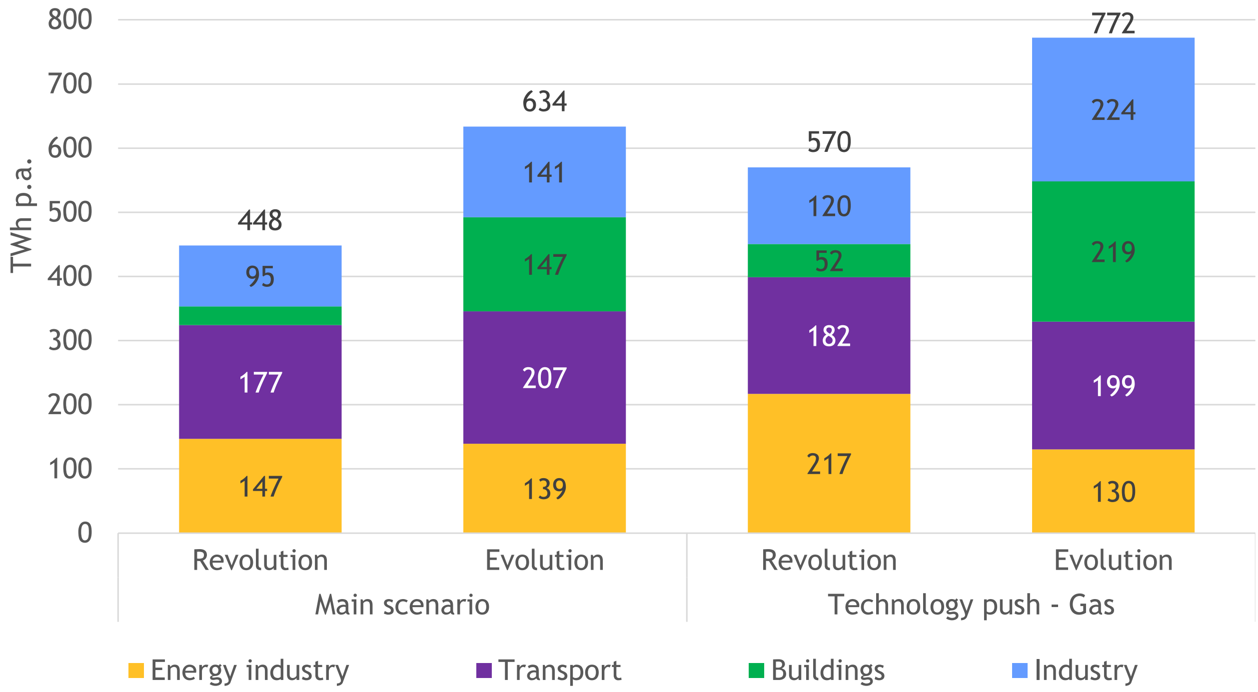

FIGURE 54: USAGE OF SYNTHETIC FUELS IN THE YEAR 2050 BY SECTOR IN THE MAIN REVOLUTION AND EVOLUTION SCENARIOS AND WITH TECHNOLOGY PUSH - GAS

Figure 55 shows the cumulative differences in total costs between the Revolution and Evolution scenarios in the main scenario and with Technology push - Gas. The cost advantage of the Evolution scenario over the Revolution scenario in the event of Technology push - Gas, can be increased in particular by a greater cost difference for capital costs, network costs and costs for Power-to-X imports. In contrast, when it comes to operating costs, fuel costs and costs for electricity imports, the Evolution scenario with Technology push - Gas loses out to the Revolution scenario, compared with the main scenario. However, the total cost advantage of the Evolution scenario over the Revolution scenario can be increased by approximately €54 billion, if the Technology push - Gas occurs.

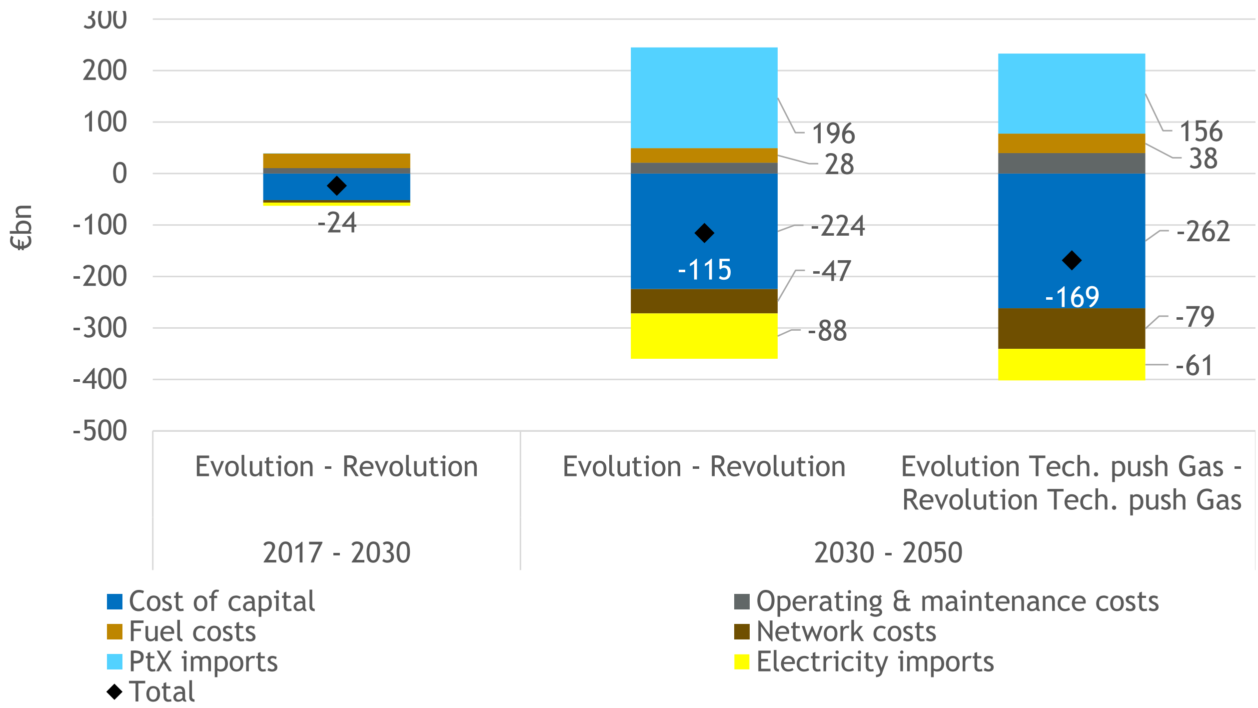

FIGURE 55: CUMULATIVE TOTAL COST DIFFERENCE OF THE MAIN SCENARIOS AGAINST TECHNOLOGY PUSH - GAS

5 THE VALUE OF EXISTING NETWORK INFRASTRUCTURE FOR EFFICIENT CO_2 REDUCTION

The value of the existing gas and heat infrastructure for efficient achievement of the CO_2 reduction targets can be inferred from the analyses in Chapters 2, 3 and 4:

1. The existing gas and heat networks permit cost-efficient achievement of the climate targets between now and 2030.

Gas heating systems and district and local heat (frequently supplied by gas CHP) represent the cheapest CO_2 reduction option in the Building sector, as is shown by the optimally computed developments in the Evolution scenario. Gas and heat networks allow the supply of final energy in order to use these established technologies. Since a large number of end-use consumers can be supplied by the existing gas and heat infrastructure without the need to expand them to any significant extent, climate targets can also be achieved with comparatively straightforward changes to the energy system. In contrast, a politically accelerated expansion of electrical applications, e.g. heat pumps, as in the Revolution scenario, would require radical changes, for example in the power station fleet and the housing stock. The Evolution scenario, which builds on the value of existing infrastructure, is cumulatively approx. €24 billion cheaper than the Revolution scenario in the period up until 2030, identical CO_2 reductions being achieved in both cases.

2. The existing gas and heat networks permit cost-efficient achievement of the climate targets between 2030 and 2050.

Even the aim of almost complete reduction of GHG in the Buildings, Industry and Energy industry sectors in 2050 can be achieved with a high penetration of gas and heat technologies, supplied by the corresponding infrastructure. This is reflected in the Evolution scenario. However, the basic prerequisite for this is the production and import of synthetic fuels and fuels produced by climate-neutral processes, which would still have to see significant cost reductions by 2050. However, in the Revolution scenario, significant demand for synthetic fuels is to be expected, for example for the reconversion of synthetic gas. Although this demand is much lower than in the Evolution scenario, it is still large enough that essential availability has to be guaranteed, even in the Revolution scenario. Because it involves fewer radical changes, the Evolution scenario is overall approximately €115 billion (cumulative from 2030 – 2050) cheaper than the Revolution scenario under the assumptions made for the future development of the technologies employed. Carbon reductions are identical in both scenarios.

3. Due to the transportability and storability of energy, the existing gas and heat networks have the advantage that far fewer radical changes are required in the energy system in order to achieve the increasingly rigorous CO_2 targets.

There are far fewer radical changes in the energy system in the Evolution scenario than in the Revolution scenario. The rapid increase in power applications in the Revolution scenario necessitates greater expansion of electricity networks, guaranteed capacity and renewables. Moreover, heat pumps often necessitate more modifications to buildings, such as the installation of underfloor heating and improved building insulation. In contrast to this, the comparatively simple storability and transportability of gas and hot water in the existing gas and heat networks means that less expansion of electricity networks, guaranteed capacity and renewables might be required in the Evolution scenario. Tried and tested systems (modernised, if necessary) can also continue to be used for end-use applications such as gas condensing boilers or heat exchangers, for example.

4. The existing gas and heat networks create an option for efficient CO_2 reduction in an uncertain and distant future after 2030 but do not exclude ex-ante any other technology options.

Viewed from the current perspective, it is impossible to predict whether, at some point in the future, e.g. after 2030, electricity-based technologies will be economically advantageous or disadvantageous in the different final energy consumer sectors relative to gas or heat-based technologies. There are numerous uncertainties such as technological progress, changing energy demand and societal trends, which can impact the energy system and hence the economic viability of technologies but it is impossible to predict these at this stage.

The analysis of two of an infinite number of possible future developments conducted in Chapter 4 highlighted two advantages of the existing infrastructure:

Firstly: even without a pre-established expansion pathway for electricity-based technologies, as assumed in the Revolution scenario, the energy system can nevertheless still react to new technological advances in electricity-based technologies at a later stage. This means that proceeding without any technology bias up until 2030 without any prior decision e.g. in favour of heat pumps, does not rule out the possibility of electricity-based heat technologies gaining a hold in the market, if corresponding technological advances are made. The results of this study show that, even in the Evolution scenario, more heat pumps and power applications will be installed, if significant progress is made in electricity-based technologies. Increased electrification of the final energy consumer sectors would mean that conventional and also synthetic fuels could be saved. Even without a prior decision regarding technology, the Evolution scenario is approximately €129 billion cheaper than the Revolution scenario, even in the event of a technology push on electricity-based applications.

Secondly: a technologically permissive pathway up until 2030 provides an opportunity to benefit from technological advances in synthetic fuels. If there is a significant technology push in gas-based technologies, such as Power-to-X plants, for example, there would hardly be any need for further electrification in the final energy consumer sectors in order to meet the climate targets. In particular, gas and oil-fired heating systems would be installed in buildings instead of heat pumps. This increases the demand for synthetic fuels but these can be produced relatively inexpensively. On the assumption of a Technology push - Gas, the cost advantage of the Evolution scenario over the Revolution scenario increases from €139 billion to €192 billion. The cost advantage of the Evolution scenario could potentially be even greater, if gas infrastructure had already been dismantled in the Revolution scenario so that there was less opportunity to take advantage of inexpensive Power-to-X fuels. This scenario is quite probable, since, as outlined in the section above, gas consumption is greatly reduced in the Building sector due to the imposed minimum number of heat pumps. The associated underuse of gas networks will lead to higher network charges or an increasing shortfall for network operators, so that they might consider dismantling gas or heat networks.

5. The existing gas and heat networks contribute to security of energy supply, since, together with the electricity network, they provide redundancy and resilience.

Apart from the economic advantage of efficient CO_2 reduction now and in the future, gas and heat networks offer a further advantage in terms of the security of energy supply. The existence of parallel energy infrastructures such as electricity, gas and heat networks, creates added value in terms of redundancy and resilience, i.e. in the event of one element of the infrastructure failing, other elements of infrastructure could help out, at least temporarily.

The one-sided focus on electricity-based technologies and hence the transport of energy solely via electricity networks creates a high level of dependence upon having a fully functional electricity network at all times. For example, in the Revolution scenario, heating of the majority of residential buildings is solely dependent upon the electricity network.

If other technology options such as gas or heat networks are also available for transporting energy, gas or oil-fired heating could always still be used, even if there were a temporary failure of the electricity network. Large quantities of oil can be stored locally and gas networks would be able to maintain the supply of gas for several days, even without any power supply, that is to say without the use of compressors, due to the residual pressure in the gas network and in the existing storage facilities.

APPENDIX 1: DESCRIPTION OF THE MODEL DIMENSION+

The DIMENSION+ energy system model optimises the short and long-term costs of providing electricity, heat and synthetic fuels across the sectors in the entire European system, taking account of any interdependencies and prevailing political, regulatory and technological framework conditions. It provides a detailed representation of the final energy consumer sectors Buildings, Industry and Transport and the Buildings and Industry sectors are also included in the cost optimisation. All calculations take account of the European electricity market. It also models the costs for expanding and operating electricity, gas and heat networks. These are based on the level and structure of the respective supply and demand.[18] Thus the model permits a coupled analysis of the electricity and final energy sectors, including infrastructures. Figure 56 schematically illustrates the causal relationships in the model.

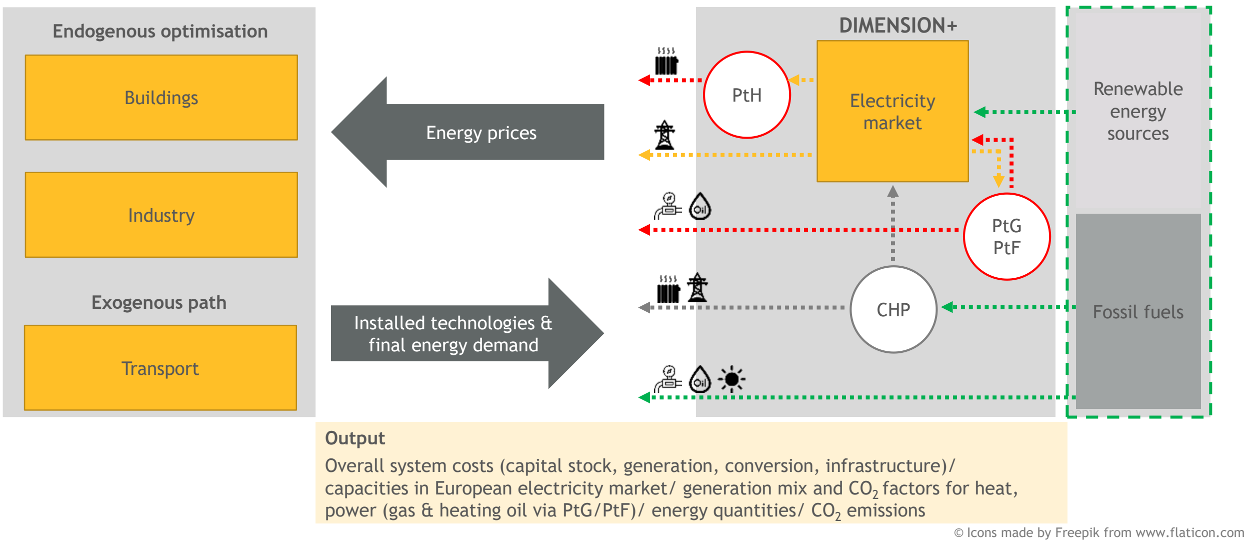

FIGURE 56: SCHEMATIC DIAGRAM OF THE DIMENSION+ ENERGY SYSTEM MODEL

Modelling of the final energy consumer sectors

Buildings

The various applications for end-use energy in the Building sector are modelled in keeping with the categories of the AG Energiebilanzen [Energy Balances Working Group] (AGEB 2017a) applications. For this purpose the German housing stock is subdivided into residential buildings (RB) and non-residential buildings (NRB). The demand for space heating and hot water is then broken down according to the type of building (detached house, duplex, apartment block or different types of NRB). The electricity used for other applications (e.g. lighting and ICT) is collated separately for RB and NRB and projected in keeping with energy efficiency assumptions. This breakdown gives approximately 50 classes of building types.

[18] A more detailed description can be found in Appendix 2.

The DIMENSION+ optimisation model can now endogenously invest in insulation and a new heating system for the different types of building and thus determine the amount of energy required and also the energy carriers. Heating systems (e.g. gas condensing boilers and air heat pumps) produce heat from the corresponding energy carriers with a set efficiency and can therefore cover the demand for space heating and hot water for the building. Investment costs for the heating system depend upon the type of building and decrease over time. Insulation technologies (partial or complete renovation) reduce the heat demand of the building and, together with the corresponding investment costs, depend upon the type of building.

Apart from the energy quantities and energy carriers, the composition of fuels from conventional, biogenic or synthetic fuels are endogenously determined against the background of the respective GHG reduction target.

Heat and electricity demand are broken down according to type of usage (space heating, hot water) with temperature patterns into hourly end-use energy consumptions for electricity and district heat (including local heat) and seasonal demand for gas, oil and biomass, which the energy system must provide at the appropriate time.

Industry

For the purpose of modelling the Industry sector, energy-intensive processes are explicitly represented with their individual production steps, so that a consistent development of energy consumption, of non-energy consumption of primary energy carriers and process emissions can be mapped on the basis of production quantities. This includes the production processes for the following industrial products:

- Steel
- Aluminium
- Copper
- Ammonia
- Chlorine
- Ethylene
- Cement
- Lime
- Glass
- Paper

Various process routes are modelled for each of these production processes, each resulting in a different usage of primary and secondary energy. The breakdown of production into the individual process routes is selected for the initial years on the basis of data from the branches and calibrated against AGEB Energiebilanzen 2015 (AGEB 2017b). Building on this, the future exogenous development pathways are assumed, in order to model innovations and technological developments.

Apart from the explicitly modelled production processes, the remaining energy consumption is aggregated, differentiated by branch, on the basis of the assumed growth of gross value added. The branches are differentiated on the basis of their energy balances. In addition, exogenous development pathways are assumed for the development of energy efficiency.

Based on the modelled energy demand of Industry, a substitution of the energy carrier's electricity and gas is represented emerging endogenously from the model. For this purpose it is assumed that, within the modelled production processes, gas-based heat production can be replaced by electricity-based heat production in the form of Power-to-Heat technologies, such as heater rods, for example. Process-specific substitution potentials are assumed in the optimisation.

Load profiles for electricity, district heat (including local heat) and heat are determined using load profiles and the potential for shift in the specific branches.

Transport

The Transport sector is projected using a comprehensive bottom-up model. For this it is divided into road transport (including cars, light duty vehicles, lorries) rail transport, inland navigation and air transport. The individual groups are updated with assumptions about the developments of transport modes, vehicles, mileages and propulsion efficiency with the aid of a fleet allocation model based on fleet inventory, service lives and registrations per annum. The final energy consumptions are then derived from the vehicle development and broken down into annual charging requirements for electricity.

Energy industry

In the model, the aggregated energy demands of the individual final energy consumer sectors is covered by the Energy industry at minimal cost. The costs of producing electricity, heat and synthetic fuels emerging from the model and the procurement costs for energy carriers (conventional, biogenic, synthetic fuels imported from outside the EU) are taken into account. Moreover, the supply and demand for electricity and heat must coincide on an hourly basis. Figure 57 contains a schematic representation of the Energy industry model.

Apart from the provision of energy quantities (electricity, district heat and energy carriers), DIMENSION+ also models a guaranteed peak capacity for the electricity sector, which emerges from the model from the electricity demand for the individual applications (e.g. heat pumps, electric vehicles) in the individual consumer sectors in accordance with usage profiles and simultaneity factors. Thus, for example, the peak load that must be guaranteed increases endogenously with increasing electrification of the heat supply. The cross-sector peak load is then aggregated using simultaneity from the peak loads of the different sectors. This peak load demand must then be covered by the corresponding technologies on the supply side. Apart from conventional power stations, these technologies also include storage and batteries as well as demand-side management measures. Based on historical data, offshore wind can contribute to guaranteed capacity to the tune of 10% of installed capacity, whereas photovoltaics and onshore wind are unable to contribute at all.

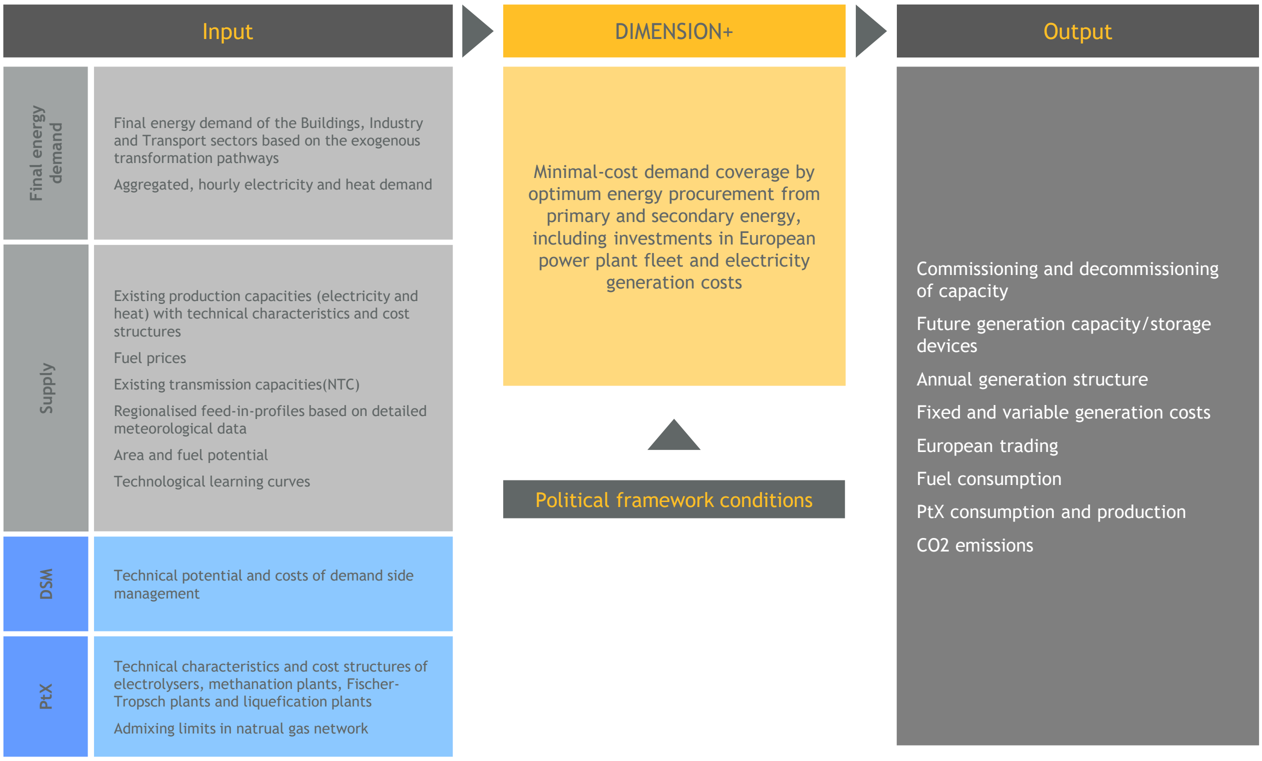

FIGURE 57: SCHEMATIC REPRESENTATION OF MODEL OF THE ENERGY INDUSTRY

In order to represent periods without any sun or wind, it is assumed that a situation with very low feed-in from PV or wind power prevails for 14 days, while outside temperatures are simultaneously low. Based on historical data, it was determined that, in such a situation, batteries would not be able to contribute, since they can only store small quantities for short periods. However, in a cold spell without sun or wind, there is high demand over a relatively protracted period. Demand-side management measures are likewise unable to help. According to historical data, PV and wind are only able to contribute 3% – 10% of their capacity during a period with no sun or wind. The demand side of the load during a period without sun or wind, is modelled for households for a two-week cold snap, with the associated increase in heat demand. Depending upon the heating system, this transfers the demand for capacity into the gas, district heat or electricity market. Transport and Industry only require their average capacity during a period with little sun or wind.

Synthetic fuels

Synthetic fuels can be used to achieve the GHG emission assumed in the model and used instead of conventional or biogenic fuels. Synthetic fuels can be modelled in the DIMENSION+ energy system model by various technologies. On the one hand, it emerges from the model that, in Europe, we can invest in Power-to-X plants such as electrolysers, methanation plants or plants for Fischer-Tropsch synthesis. Hydrogen, Power-to-Gas or various Power-to-Fuels can then be produced with electricity, other inputs such as CO_2 being necessary in some cases. Account is also taken of the fact that a small percentage of pure hydrogen can also be injected directly into the gas network, so that the intermediate methanation step can be omitted. Apart from endogenous production within Europe, there is also the option to import synthetic fuels at full cost from countries outside Europe. Synthetic fuels provide the opportunity for exploring and comparing non-technology-specific alternatives for reducing GHG emissions by electrification of all sectors.

Costs

Costs for investment in heating systems and insulation are considered for the Buildings final energy consumer sector, in accordance with the assumptions made about expected lifetime and cost reduction.

In the case of the Transport final energy consumer sector, the cost of investments in new transport technologies are not included in the optimisation, so that an identical development can be assumed for the Transport sector in both scenarios.

Moreover, the optimisation considers the total system costs of the energy system for energy conversion, storage and consumer facilities, such as network infrastructure, as well as energy quantities and GHG emissions on the cost side and optimises these.

Model results

As illustrated in Figure 57, various results can be read out from the DIMENSION+ model after the optimisation procedure. Apart from quantities of GHG in CO_2 equivalent by sector according to the source principle, these also include the development of power station capacities in the European electricity market and all energy quantities and flows (e.g. fuel usage by power station type, Power-to-X production, energy imports/exports). Moreover, the arising costs can be considered and analysed in detail.

APPENDIX 2: METHODOLOGY FOR INFRASTRUCTURE COSTS

Electricity networks

The electricity networks costs modelled in this study arise from capital costs, operating and maintenance costs and other miscellaneous costs. BNetzA data on upper revenue limits (BNetzA 2017), the Monitoringbericht 2016 (BNetzA and BKartA 2016), results of network simulations conducted as part of the geea-Gebäudestudie (geea 2017) and the estimates made by Hinz et al. (2014) are used for modelling costs. The need to expand the electricity network is a particularly critical factor, since significant expansion of the electricity network is envisaged, due to the changing generating structure and scenario-dependent electrification of the final energy consumer sectors. The necessary investment costs are estimated on the basis of the said sources and the electricity demand (output and capacity) and expansion of renewables determined in the DIMENSION+ model. Expansion costs of €272 billion by 2050 were determined for the Revolution scenario and €219 billion for the Evolution scenario. In this study, expansion follows an established expansion pathway. The arising investment costs are converted into capital costs on the basis of the interest rates and service lives defined in the Electricity Network Charges Ordinance (StromNEV). In the case of investments that have already been made, it is assumed that these arise uniformly over the period and that depreciation periods are the same as at present. This leads to a drop in capital costs for legacy investments over the period.

Since estimating future operating and maintenance costs and miscellaneous costs, such as re-dispatch, for example, would require a huge amount of effort and goes beyond the scope of this study, costs are assumed to be constant. However, it is to be assumed that these costs would be higher in a scenario with greater network expansion. The additional costs of the Revolution scenario relative to the Evolution scenario are therefore generally underestimated. The transmission and distribution network costs determined for the two scenarios are shown in Figure 58 and Figure 59.

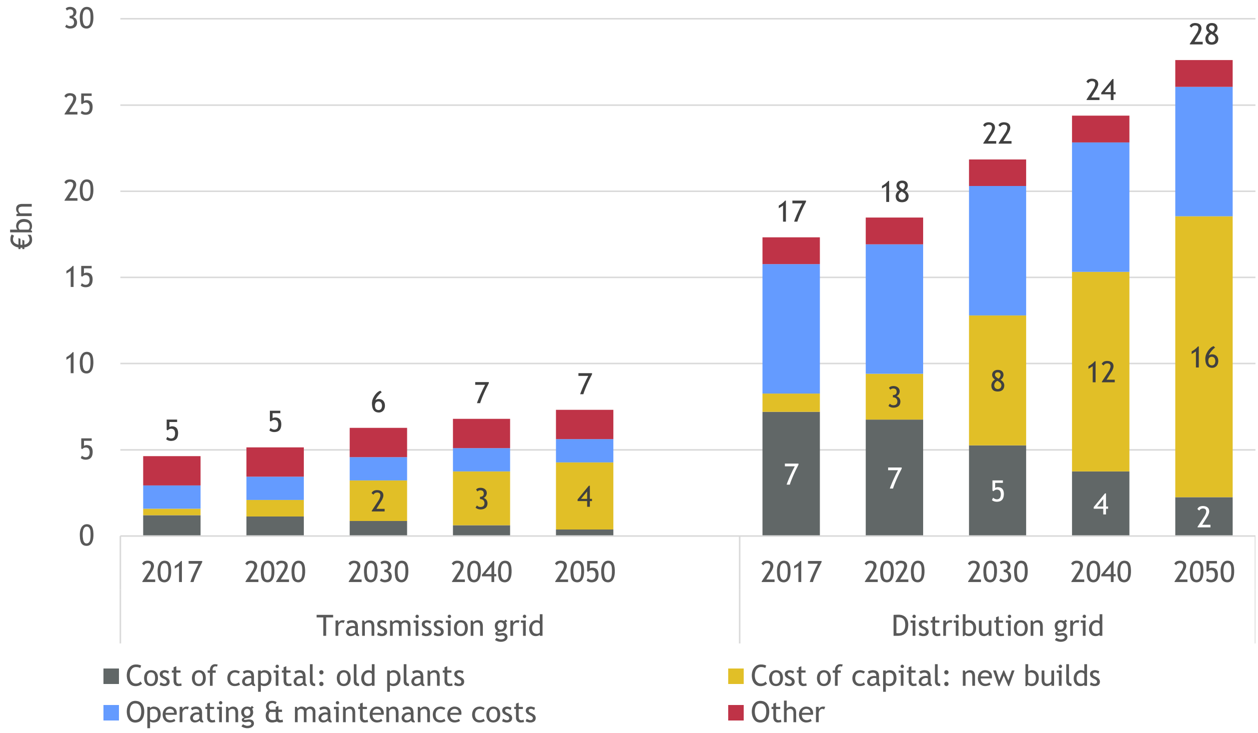

FIGURE 58: ANNUAL ELECTRICITY NETWORK COSTS BY COST TYPE IN THE REVOLUTION SCENARIO

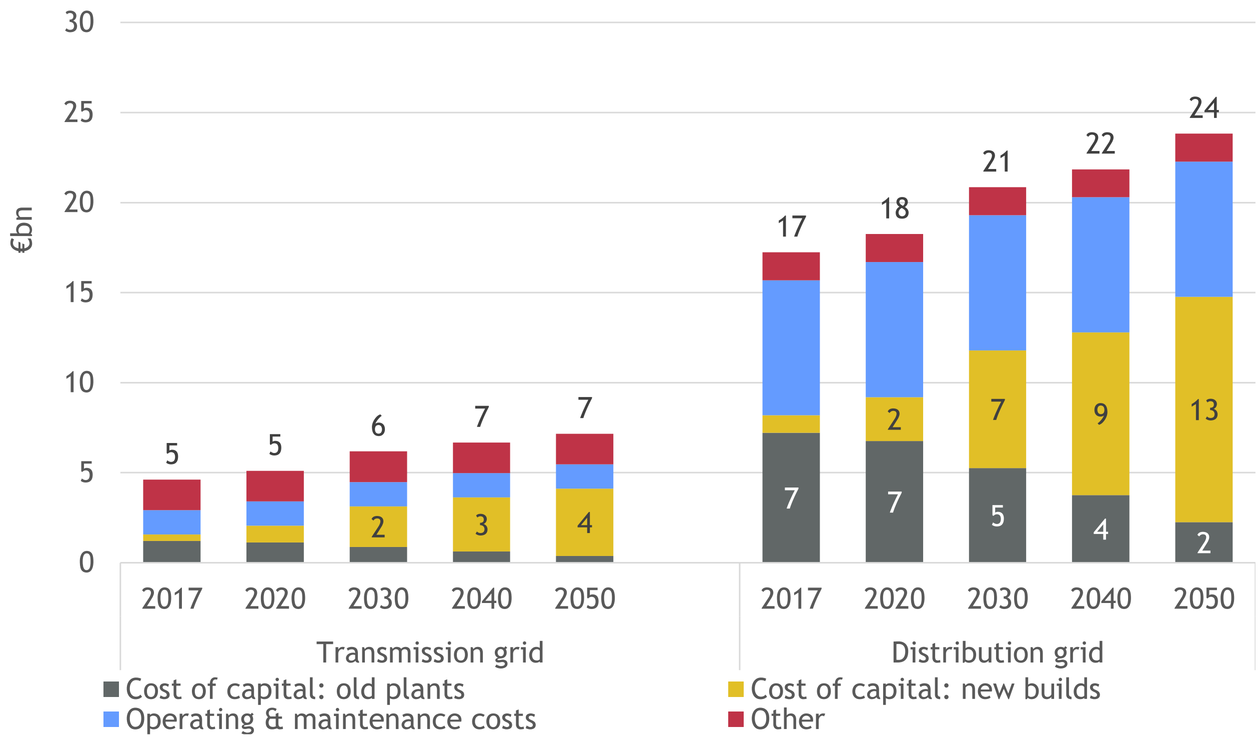

FIGURE 59: ANNUAL ELECTRICITY NETWORK COSTS BY COST TYPE IN THE EVOLUTION SCENARIO

Gas networks

The costs for gas networks are modelled in more or less the same way as costs for electricity networks. Costs are broken down into capital costs, fixed and variable operating and maintenance costs. The capital costs are estimated by assessing new investments based on the 2016 Network Development Plan (Netzentwicklungsplan) (FNB Gas 2016), the Monitoringbericht 2016 (BNetzA and BKartA 2016) and data from gas network operators, as well as the gas demand of the individual customer groups determined in DIMENSION+ for the Revolution and Evolution scenarios. These investments are converted into capital costs based on the interest rates and service lives defined in the Gas Network Charges Ordinance (GasNEV). In the case of investments that have already been made, it is assumed that these arise uniformly over the period and that depreciation periods are the same as at present. Variable costs (primarily for propellant gas) are derived from data from transmission system operators and the DIMENSION+ results for the Revolution and Evolution scenarios.

Additionally, dismantling costs are estimated on the basis of expert interviews and the model results. However, since this estimate is associated with various uncertainties, these costs are not included in the cost calculation in Chapter 2.6 and Chapter 3.6. Consequently, the costs of the Revolution scenario are generally underestimated, since partial dismantling of the distribution networks is likely in this scenario, due to the much smaller demand for gas from households and industry.

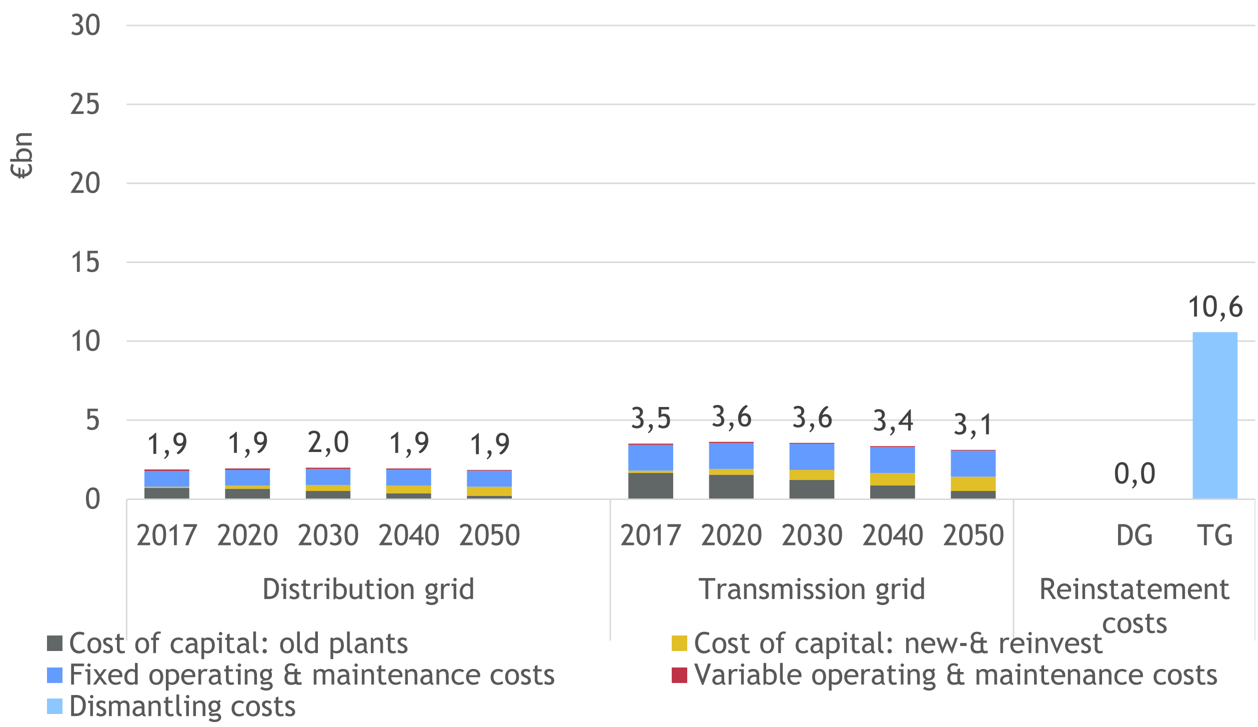

FIGURE 60: ANNUAL GAS NETWORK COSTS BY COST TYPE IN THE REVOLUTION SCENARIO

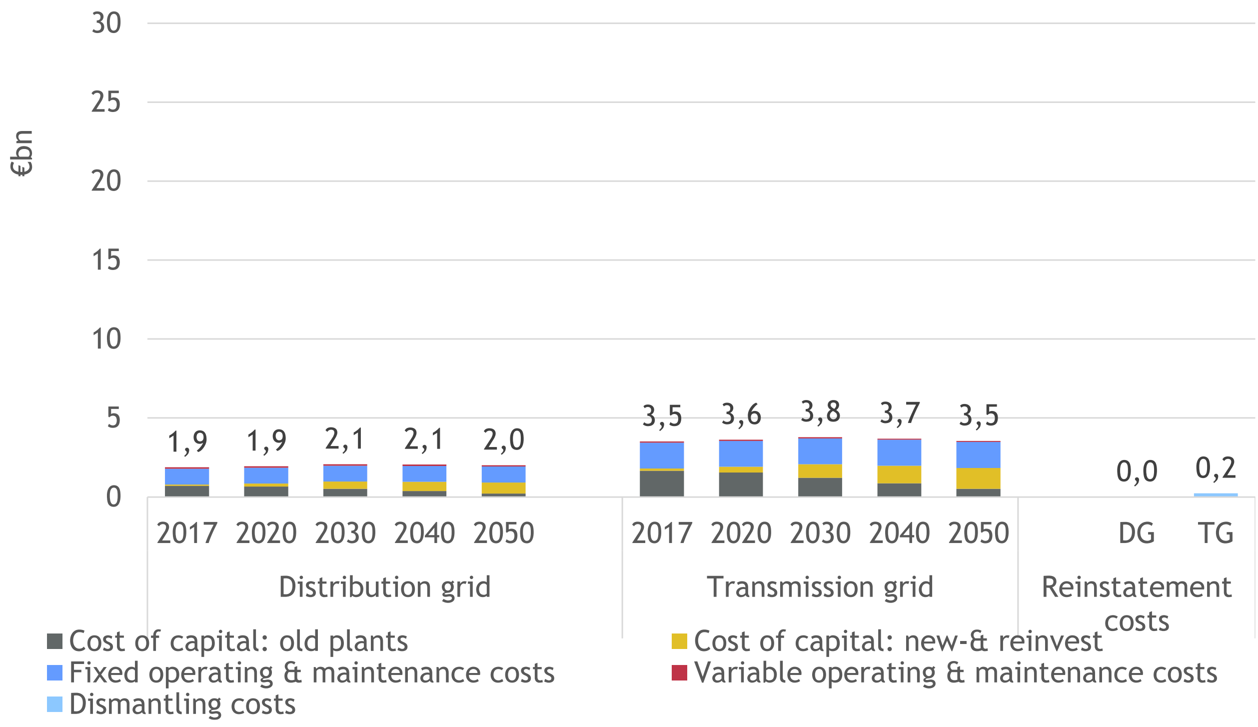

FIGURE 61: ANNUAL GAS NETWORK COSTS BY COST TYPE IN THE EVOLUTION SCENARIO

Heat networks

Since less data is available for heat infrastructure, the costs are modelled using a simplified mechanism. This is based on the results obtained by Eikmeier (2014). Fixed and variable costs are considered in the calculation and a distinction is also made between heat networks for process heat and heat networks for space heating and hot water.

APPENDIX 3: ASSUMPTIONS AND DATA

In order to analyse the energy market in 2030 and 2050, it is necessary to make assumptions about the future world. The assumptions for the central framework parameters for this study are outlined and discussed below. First of all, the cross-scenario parameter assumptions are explained, followed by the scenario-specific parameter assumptions.

Cross-scenario parameter assumptions

Macroeconomic parameters

a) Population growth

In accordance with the study entitled "13. Koordinierte Bevölkerungsvorausberechnung" [13th coordinated population forecast] from the Federal Office of Statistics (destatis 2015a), it is assumed that Germany has 80.9 million inhabitants in 2030 and 76.1 million inhabitants in 2050. This assumption influences energy demand in the Buildings and Transport sector.

b) Economic growth

The assumed per capita economic growth corresponds to the historical annual growth in gross domestic product (GDP) for the years 1992 – 2016 (destatis 2016) of 1.4% per head of population. Due to the slight decline in population, annual GDP growth rates of between 0.9% and 1.4% are obtained.

c) Energy carrier prices

It is assumed that, in the light of the ambitious national climate protection plans, the demand for fossil fuels only increases moderately and there is high availability of resources. Consequently the chosen fuel prices for oil, coal and natural gas are the same as in the WEO New Policies Scenarios (IEA 2016). The data corresponds to real prices in US dollars (USD), converted into current euros (base year 2016) on the basis of a constant exchange rate of 0.833 USD/EURO. Since WEO 2016 only forecasts prices up until 2040, a constant price development is assumed from 2040 onwards. The fuel prices assumed for this study are shown in Figure 62.

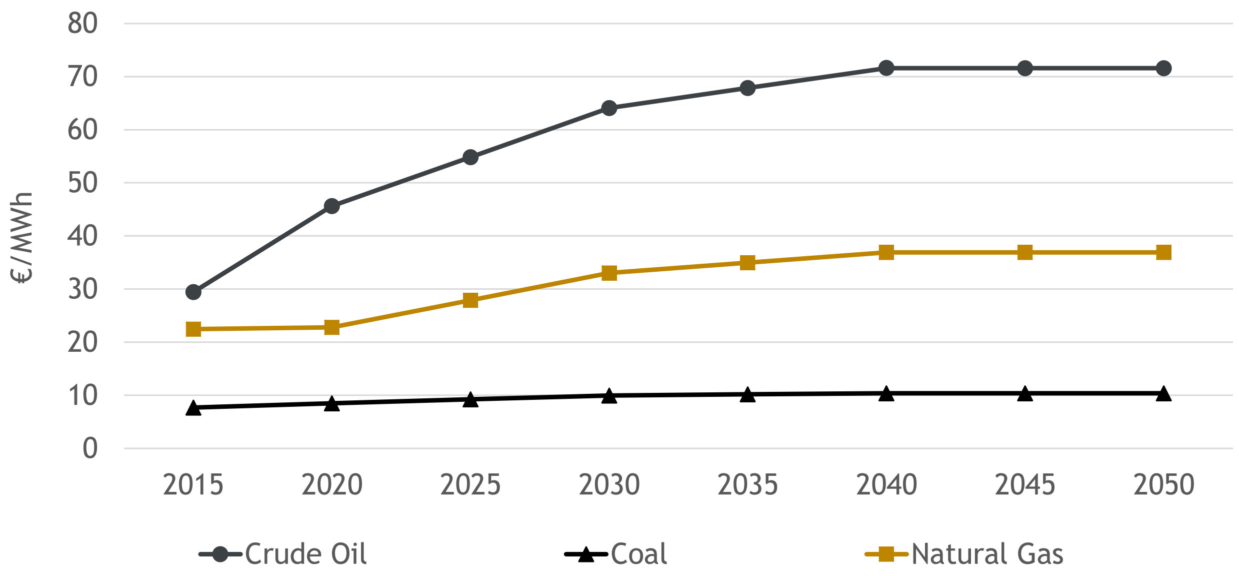

FIGURE 62: CROSS-SCENARIO ASSUMPTIONS FOR ENERGY CARRIER PRICES

Source: Own graph based on WEO 2016 - New Policies Scenario

Generation sector

a) Minimum expansion targets and potential area for renewables

It is assumed that the expansion targets decided in EEG 2017 are achieved by 2030. The resulting trend is continued up until 2050 and is shown in Table 3. However, against the background of the highly ambitious CO_2 reduction targets assumed in this study, these variables do not constitute restrictive assumptions. The minimum targets for all renewables are overfulfilled in both the Revolution and the Evolution scenario.

Installed capacity [GW]	2015	2020	2025	2030	2035	2040	2045	2050
Biomass	6,9	7,6	8,6	9,6	10,1	10,6	11,1	11,6
Onshore wind	41,2	54,6	69,1	83,6	90,9	98,1	105,4	112,6
Offshore wind	3,4	6,5		15,0	17,1	19,3	21,4	23,5
PV	39,3	51,8	64,3	76,8	83,1	89,3	95,6	101,8

TABLE 3: CROSS-SCENARIO MINIMUM CAPACITIES OF RENEWABLE ENERGY PLANTS

On the other hand, potential available surface area is assumed for the purposes of this analysis. This constitutes the technically, ecologically and socially acceptable limits on potential for expanding renewable electricity generation plants. The parameter for base PV is based on an analysis of potential by the BMVI, which takes account of restrictions imposed by the conflicting demands for using available land for renewables or agriculture, residential space and nature conservation (cf. BMVI 2015). According to this, 3,164 km² are available for use for base PV. Potential PV roof space was determined on the basis of the same source. Here the central variable is the available roof space on residential and non-residential buildings. According to this, 1,050 km² are available for use for roof PV.

Onshore wind	10.005 km²
Offshore wind	47.000 km²
Base PV	3.164 km²
Roof PV	1.050 km²
Potential biomass for energy use	250 TWh/a

TABLE 4: LIMITS ON POTENTIAL OF RENEWABLE ENERGIES IN GERMANY

Sources: BMVI 2015, DEWI 2013, UBA 2014

The potential of onshore wind is determined from the availability of land as a function of the prescribed minimum spacing, as an indicator of social acceptance. It is assumed that a surface area of 10,005 km² is available for onshore wind turbines. With a surface usage of 56 km²/GW according to BWE (2013), it is possible to add up to 179 GW. If one assumes that an average wind turbine has a capacity of 3 MW in 2050 (as opposed to the average 1.7 MW today), this corresponds to more than a doubling to approximately 60,000 onshore wind turbines in 2050 (as opposed to 27,270 today). Thus, if Germany were to be divided into a quadratic grid, on average there would be a wind turbine every 2.4 km.

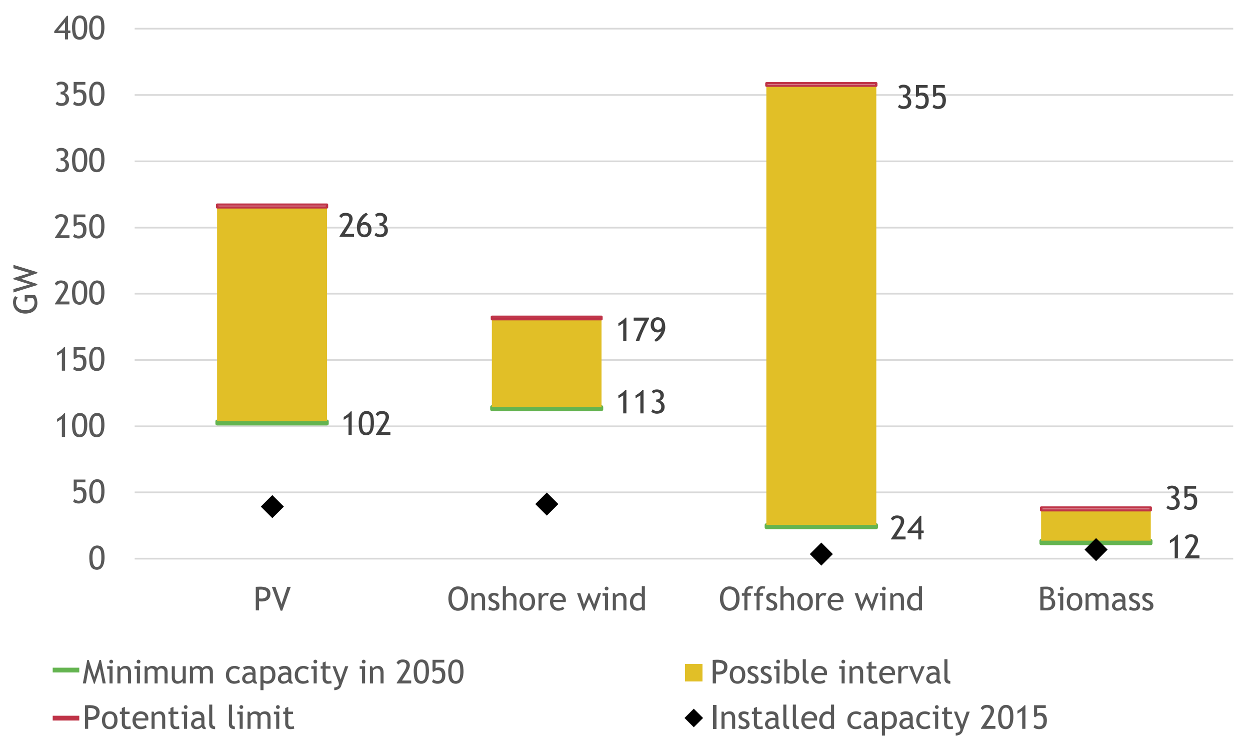

FIGURE 63: CROSS-SCENARIO ASSUMPTION FOR MINIMUM EXPANSION UP UNTIL 2050 AND LIMITS ON POTENTIAL

In addition to the potential surface area for photovoltaics and wind energy, limits on potential are also considered for energy produced from biomass. According to UBA (2014), Germany has a biomass potential for energy use of 202 TWh from solid fuels and biogas. Assuming an average utilisation of 82.5%, this gives a maximum installed capacity of 28 GW. This takes account of the socio-economic limits of land-intensive energy production from cultivated biomass in competition with alternative agricultural usage. It is assumed that up to 48 TWh p. a. of biogenic fuels are imported from abroad, making a total energy production from biomass of 250 TWh p. a. possible in Germany. The limits on potential used in this study, based on the reference sources, and the minimum capacities in 2050 are shown in Figure 63.

b) Investment costs for wind and PV

Investment costs for photovoltaics and wind power are based on the Agora Energiewende studies (2013, 2015 and 2016). Due to the recent decline in the cost of solar panels, investment costs for Photovoltaics Base and Photovoltaics Roof are assumed to be relatively low compared with these studies. The selected investment costs are shown in Figure 64.

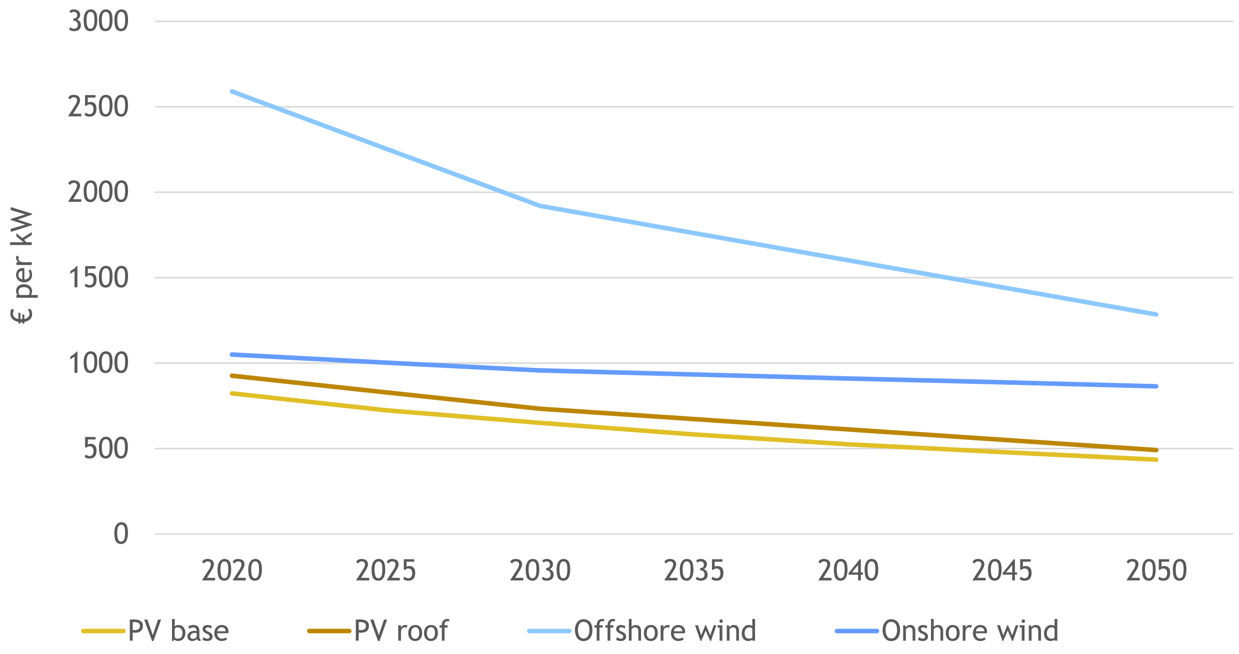

FIGURE 64: CROSS-SCENARIO INVESTMENT COSTS FOR WIND AND PV

c) Phasing-out nuclear energy and coal

In both scenarios it is assumed that the decision that has already been made to phase out nuclear energy is carried through.

The mandatory phase-out of coal is not assumed for the purposes of this study. However, this assumption is less critical, since the use of coal will increasingly decline in both scenarios as a result of the ambitious national greenhouse gas reduction targets. No coal or hard coal is used in 2050 in either scenario.

Industry sector

The assumptions for the Industry sector are based on a number of sources and expert interviews. The most relevant sources for modelling process characteristics, including their energy consumptions, CO_2 emissions and potential for substitution are Dechema (2017) and Fraunhofer ISI (2013). Information relating to current production quantities and the current type, level and breakdown (by process) of energy demand in the individual branches of industry is primarily based on Fraunhofer ISI (2016). It is assumed that the value created by the Industry sector is in line with the development of overall economic performance and thus increases by between 0.9% and 1.4% a year. The development of production quantities in the energy-intensive Industry sector is always assumed to be above the level of economic growth. It is 1.6% for the first years modelled and drops to 1.1% by 2050.

Building sector

The structure of the current building stock (detached houses, duplexes, apartment blocks, as well as commercial and industrial property, taking account of the respective age structures) is based on our own calculations from the dena buildings report (dena 2016) and the building and heating technology database set up by BDEW (2013). Exogenous building and demolition is assumed for the individual building types in both scenarios. In each case, the pathways are based on current building and demolition rates from the German Federal Office of Statistics (destatis 2015b and destatis 2017) and on forecasts from UBA (2016) and IWO (2013).

Transport sector

The model maps the Transport sector in detail, taking account of all relevant modes of transport and technologies. Since the Transport sector is not the main focus of this study, an identical course is assumed in both scenarios. It is assumed that there is a slight increase in vehicle mileage for cars (from 606.5 billion km in 2015 to 628.8 billion km in 2050) and light duty vehicles (from 43.1 billion km in 2015 to 50.2 billion km in 2050). These assumptions are based inter alia on a study conducted by the EU Commission (2013). In contrast, efficiency gains in the individual vehicle categories are assumed, based on the results of the long-term scenarios from DLR, IWES and IfnE (2012). Estimates of capital and operating costs are based inter alia on the result of Dodds and McDowall (2014) and the data from the EU Reference Scenario (EU Commission 2013). It is also assumed that there is significant electrification of the private car and light duty vehicle sectors. The percentage of electric cars and light duty vehicles in this study is 25% in 2030 and 70% in 2050. This gives rise to an electricity demand of 28 TWh in 2030 and 69 TWh in 2050. Against the background of increasing globalisation, the trend of increased demand for freight transport continues. It is further assumed that greater electrification does not take place in freight transport but instead more use is made of gas and liquefied natural gas (LNG).

Scenario-specific parameter assumptions

This section describes the parameter assumptions, which are different for the Revolution scenario and the Evolution scenario.

Building sector

a) Number of heat pumps

Evolution
The optimal number of heat pumps is endogenously determined in the model. No minimum number is prescribed.

Revolution
The key element of the Revolution scenario is reducing GHG in Germany by means of electrification. More extensive installation of heat pumps is essential for this. The obligatory number of heat pumps corresponds to the figures given by Agora Energiewende (2017) for achieving climate protection targets. This number is 6 million for 2030 and 13 million for 2050.

b) Renovation rate

Evolution
The optimal renovation rate is endogenously determined in the model. No minimum renovation rate is prescribed.

Revolution
A renovation rate of 2% is prescribed in the Revolution scenario. This is necessary because, in order to operate efficiently, heat pumps require low system temperatures, which presuppose a higher level of insulation of the building envelope in the housing stock.

c) District heat

Evolution
It is assumed that the volume of district heat (including local heat) can be increased by 30% in the existing network by the year 2030. This is achieved on the one hand by increasing the connection rate (20%) and on the other by extending lines into development areas (10%).

Revolution
It is assumed that district heat (including local heat) is displaced to some extent by the focus on heat pumps. This reduces the option for using heat by 13% by 2030 and by 45% by 2050.

Industry sector

a) Electrification of process heat production

Evolution
No minimum percentage of electrified process heat is assumed.

Revolution
It is assumed that the regulatory requirements will stipulate minimum percentages of electrified process heat in Industry as a function of temperature level.

	2015	2020	2025	2030	2035	2040	2045	2050
< 100°C	12%	18%	25%	35%	45%	60%	75%	90%
100-500°C	9%	15%	20%	25%	30%	40%	50%	60%
500-1.000°C	9%	10%	13%	15%	18%	20%	25%	30%
> 1000°C	7%	7%	8%	10%	13%	15%	18%	20%

TABLE 5: MINIMUM PERCENTAGES OF ELECTRIFIED PROCESS HEAT BY TEMPERATURE LEVEL IN THE REVOLUTION SCENARIO

Parameter assumptions for analysis under uncertainty

This section describes the parameter assumptions, which differ between the scenarios Technology push - Electricity and Technology push - Gas and an average development. They are used in Chapter 4 to analyse the uncertain technological developments between 2030 and 2050. In each case, the parameter assumptions are based on an assessment of relevant and current studies. The average development pathway is oriented towards the studies that tend to expect lower cost reductions. The Technology push - Electricity and Technology push - Gas sub-scenarios are oriented towards the more optimistic study results.

Technology push - Electricity

a) Investment costs for brine/water heat pumps

The investment cost pathways for brine/water heat pumps in the main scenarios (average development) and in the Technology push - Electricity sub-scenario are based on studies from Fraunhofer ISE (2015), IEA (2010), DLR, IWES, IfnE (2012) and DLR (2015) and are illustrated in Figure 65. The cost advantages of the Technology push - Electricity variant over the average development are around 10% in 2030 and increase to 20% by 2050.

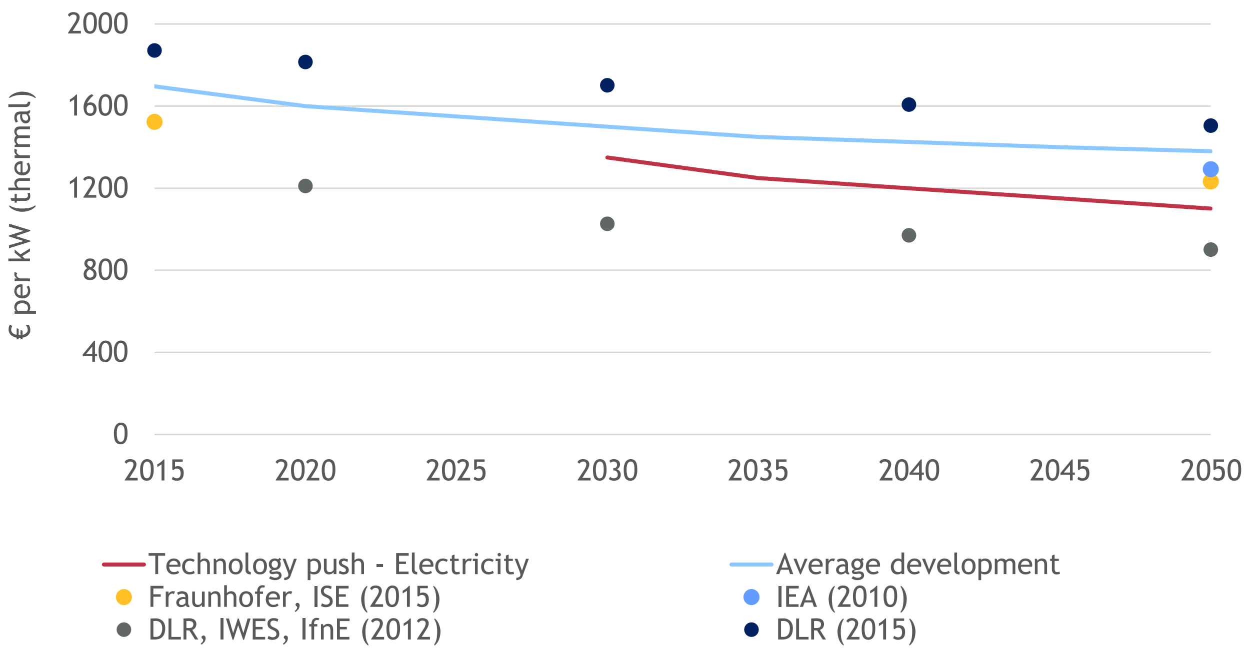

FIGURE 65: DEVELOPMENT OF INVESTMENT COSTS FOR BRINE/WATER HEAT PUMPS IN AN AVERAGE DEVELOPMENT AND WITH TECHNOLOGY PUSH - ELECTRICITY COMPARED WITH OTHER STUDIES

b) Investment costs for air/water heat pumps

The investment cost pathways developed for air/water heat pumps in the main scenarios (average development) and in the Technology push - Electricity sub-scenario are based on studies from

Fraunhofer ISE (2015), IEA (2010) and the Öko-Institut (2016) and are illustrated in Figure 66. The cost advantages of Technology push - Electricity over the average development are around 15% in 2030 and increase to 20% by 2050.

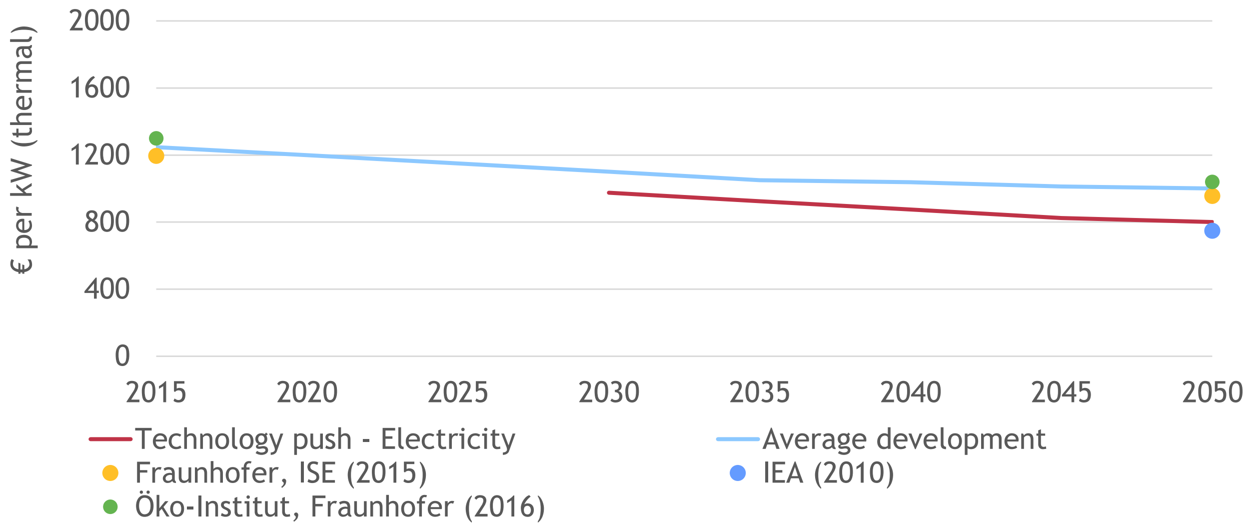

FIGURE 66: DEVELOPMENT OF INVESTMENT COSTS FOR AIR/WATER HEAT PUMPS IN AN AVERAGE DEVELOPMENT AND WITH TECHNOLOGY PUSH - ELECTRICITY COMPARED WITH OTHER STUDIES

c) Investment costs for heat storages

The investment cost pathways for heat storages in the main scenarios (average development) and in the Technology push - Electricity sub-scenario are based on studies from UBA (2016), Fraunhofer ISE (2015) and Fraunhofer IWES (2015) and are illustrated in Figure 67. The cost advantages of Technology push - Electricity over the average development are around 30% in 2030 and increase to 50% by 2050.

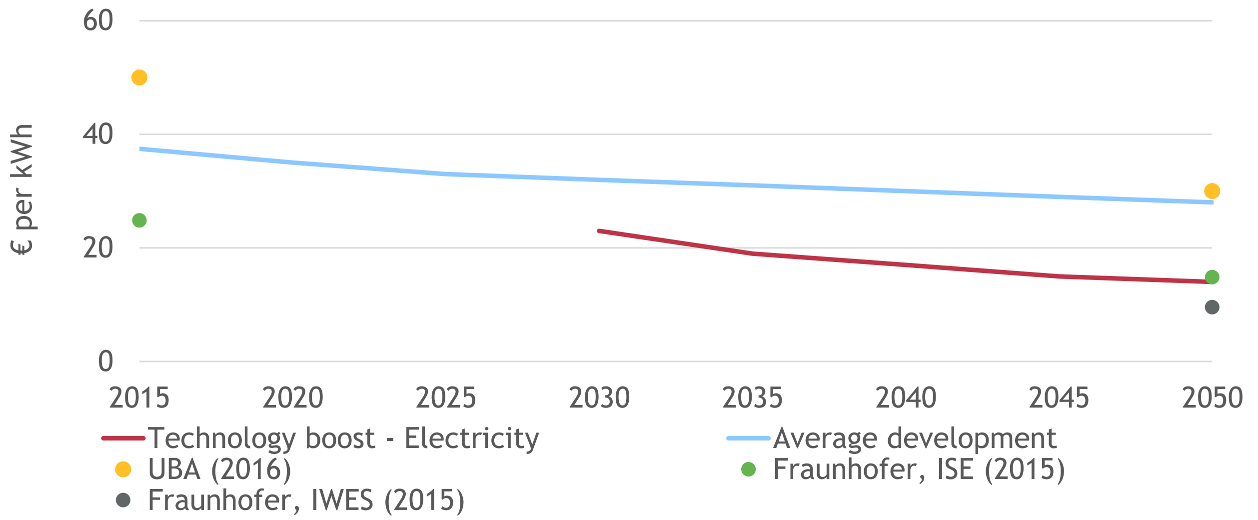

FIGURE 67: DEVELOPMENT OF INVESTMENT COSTS FOR COMBI HEAT STORAGE TANKS OF UP TO 20 M³ IN AN AVERAGE DEVELOPMENT AND WITH TECHNOLOGY PUSH - ELECTRICITY COMPARED WITH OTHER STUDIES

Technology push - Gas

a) Investment costs for electrolysers

The investment cost pathways developed for electrolysers in the main scenarios (average development) and in the Technology push - Gas sub-scenario are based on studies from Fraunhofer ISE (2015), Acatech (2015), Agora Energiewende (2014), OTH/FENES/Energy Brainpool (2015) and the Lemoine Institut (2013) and are illustrated in Figure 68. The cost advantages of Technology push - Gas over the average development are around 40% in 2030 and increase to 50% by 2050.

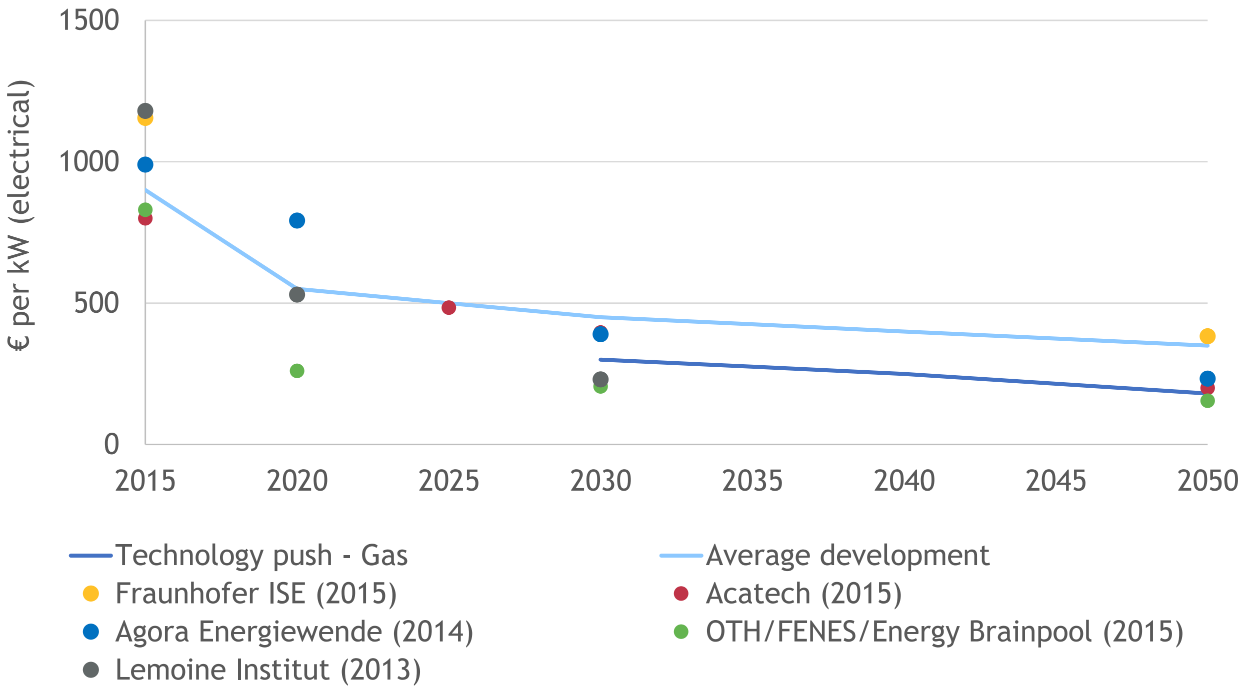

FIGURE 68: DEVELOPMENT OF INVESTMENT COSTS FOR AN ELECTROLYSER IN AN AVERAGE DEVELOPMENT AND WITH TECHNOLOGY PUSH - GAS COMPARED WITH OTHER STUDIES

b) Investment costs for combination of electrolyser and methanation plant

The investment cost pathways developed for combinations of electrolysers and methanation plant in the main scenarios (average development) and in the Technology push - Gas sub-scenario are based on studies from Fraunhofer ISE (2015), Acatech (2015), Agora Energiewende (2014), OTH/FENES/Energy Brainpool (2015), a study from DLR, IWES, IfnE (2012) and from UBA (2016) and are illustrated in Figure 69. Since the technology of methanation is not as well researched as electrolysis, the cost advantages of Technology push - Gas are slightly greater than the average development. They are around 45% in 2030 and increase to 55% by 2050.

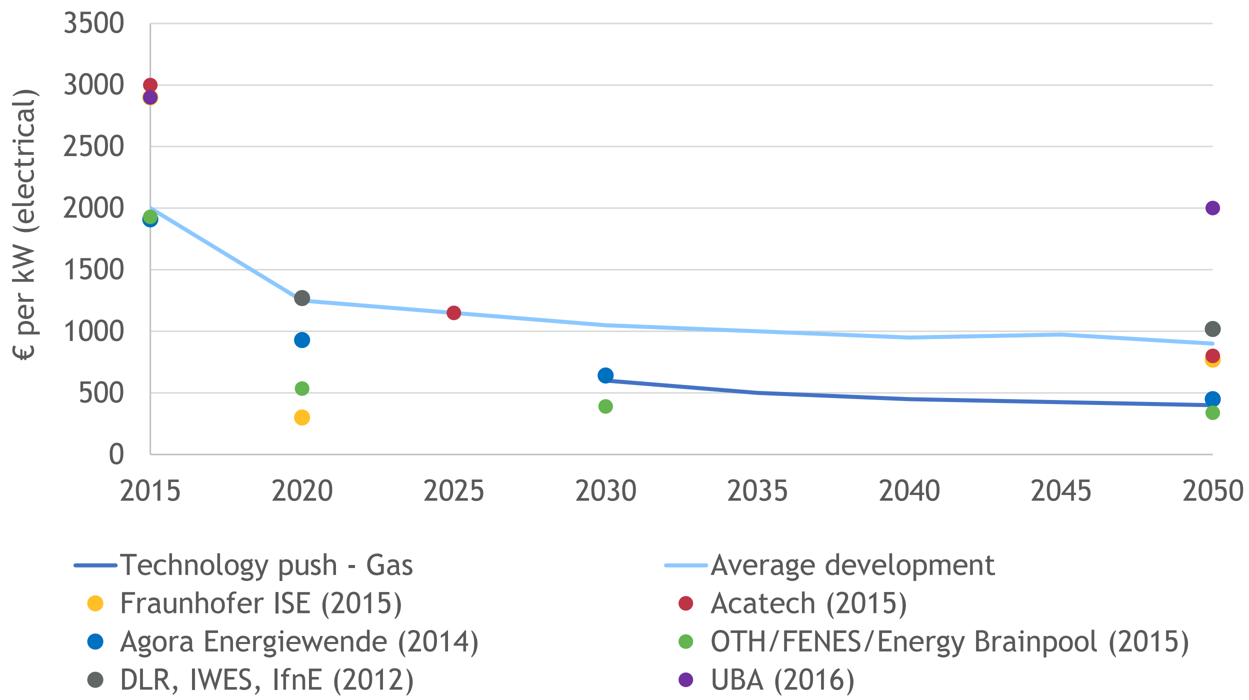

FIGURE 69: DEVELOPMENT OF INVESTMENT COSTS FOR AN ELECTROLYSER IN AN AVERAGE DEVELOPMENT AND WITH TECHNOLOGY PUSH - GAS COMPARED WITH OTHER STUDIES

c) Import costs for synthetic fuels

Costs for importing synthetic fuels from within the EU are based on the full cost of producing these fuels. The investment costs for electrolysers and methanation plants described in the previous sections and quantities of Power-to-X produced are used.
In the average development scenario, costs for importing synthetic fuels from outside the EU are based on the provisional results of the study entitled "Costs of imported synthetic fuels up until 2050" conducted by Frontier Economics (2017). The cost assumed in the Technology push - Gas sub-scenario are around 20% lower. Figure 70 shows the prices for synthetic gas imported from outside the EU.

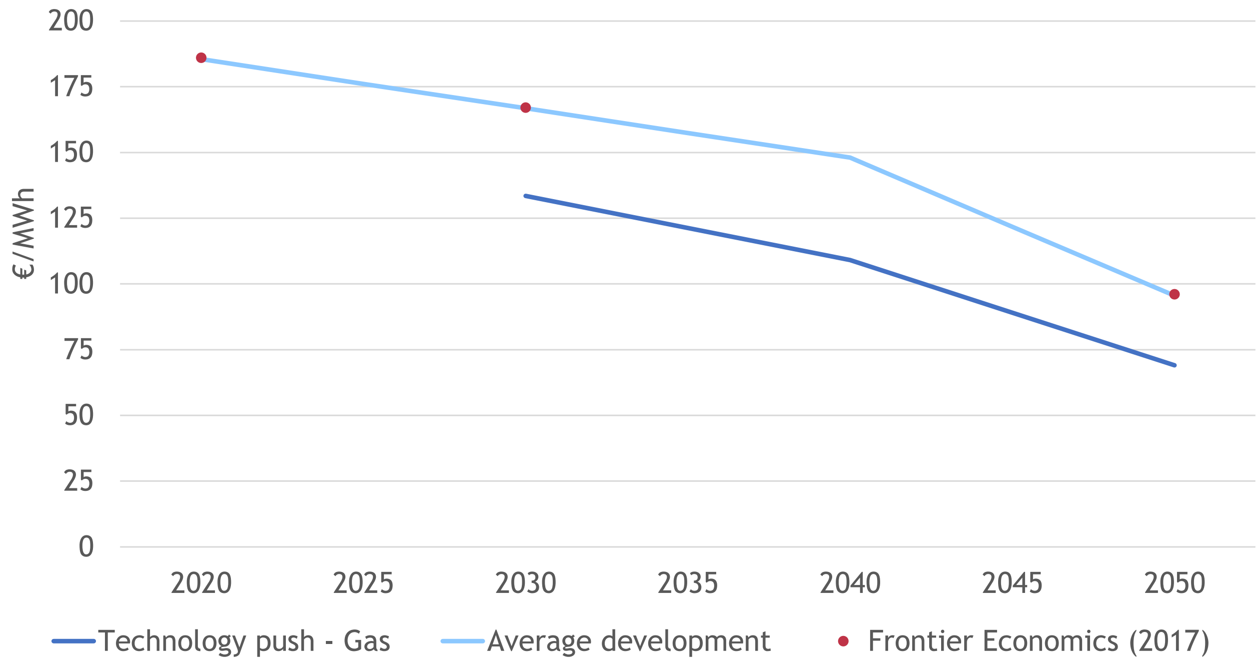

FIGURE 70: DEVELOPMENT OF IMPORT COSTS FOR SYNTHETIC GAS FROM OUTSIDE THE EU IN AN AVERAGE DEVELOPMENT AND WITH TECHNOLOGY PUSH - GAS

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