FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

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Pathways for transforming the German energy system by 2050

Considering all sectors and energy carriers, the model-based study investigates scenarios of system development and related costs to transform Germany's energy system in line with climate protection targets.

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The model REMod-D (Renewable Energy Model – Germany) was developed within a self-funded research project. Further additions to the model were carried out in both a self-funded research project as well as in the research project "Grid-interactive buildings," funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). Results presented in this study are based on the self-funded research project.

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Brief Summary

The main goal of the German energy transformation is to drastically reduce greenhouse gas (GHG) emissions. By 2050, Germany is to decrease its GHG emissions by at least 80 %, and wherever possible by 95 %, below 1990 levels. Energy-related carbon dioxide (CO_2) emissions make up the largest share of GHG emissions and account for about 85 % of the total GHG emissions in Germany today [1]. To achieve its climate protection targets, the German federal government has declared to fundamentally transform its energy system, requiring a thorough restructuring of the energy system as we know it today. This leads to the guiding question of this study: How can a cost-optimised transformation of the German energy system – with consideration of all energy carriers and consumer sectors – be achieved in line with meeting the declared climate targets and ensuring a secure energy supply at all times. We address this question in the present analysis. In this study, we assume that the nuclear phase-out is successfully achieved by 2022 according to plan and that no large-scale use of carbon capture and storage (CCS) will be implemented for decarbonizing the electricity generation from fossil fuel power plants. Besides environmental sustainability and cost-effectiveness, the model also addresses security of supply, the third aspect of the energy policy triangle, through time-resolved simulations which ensure the energy demand is met each hour throughout the entire year.

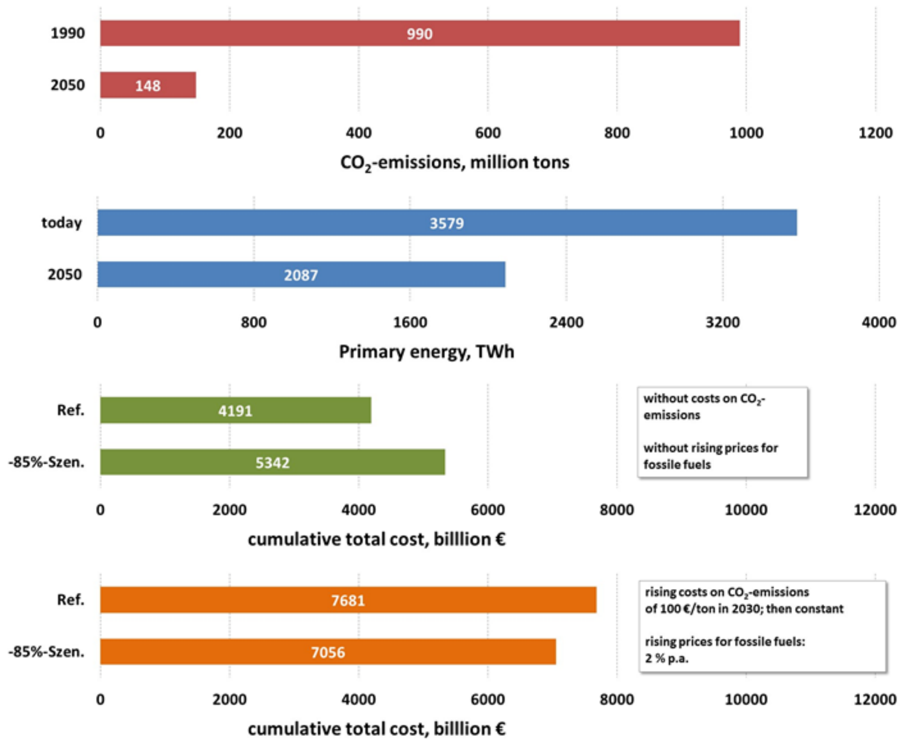


Fig. 1 Overview showing the main results from the study. Primary energy consumption, CO2 emissions and cumulative total costs for one of the scenarios investigated (85 % less energy-related CO2 emissions in 2050 than 1990 levels) are compared to the reference case which assumes that Germany's energy system continues to operate in 2050 as it does today.

Figure 1 summarizes the main results of the analysis. A future energy scenario emitting 85 % less CO_2 emissions than 1990 levels is compared with a reference scenario, which assumes that the German energy system operates in 2050 the same way as it does today. Results show that the primary energy supply for 85 % scenario will drop 42 % below today's values by 2050. Assuming that no penalty is imposed on CO_2 emissions and the price of fossil energy remains constant, calculations show that the cumulative total costs to maintain and operate today's energy system will be 27 % less than transforming the energy system to the targeted minus 85 % scenario. On the other hand, if the penalty for CO_2 emissions increases to €100/ton by 2030 and thereafter remains constant and given that fossil fuel prices increase annually by 2 %, then the total cumulative costs of today's energy system are 8 % higher than the costs required for the minus 85 % scenario up to 2050.

In the study presented here, potential pathways for the transformation are compared using various scenarios. The scenarios differ with regard to the mix of drive concepts used in the future mobility sector, the extent of the energy renovations in the building sector and the exact time at which coal-fired electricity generation is no longer used. In addition, various climate targets are considered, namely, reducing CO_2 emissions by 80 %, 85 % or 90 % below 1990 levels by 2050. Important results from our analyses are briefly summarised in the following.

The most important results concerning the structure of the future energy system are:

1. Investigations of the various scenarios show that there are a number of different transformation pathways and system configurations that enable the targeted reductions in energy-related CO_2 emissions to be met and at the same time offer technically feasible boundary conditions for renewable energy capacity.

2. For all of the investigated scenarios, the use of fluctuating renewable energy sources (primarily wind and solar PV) to generate electricity plays a key role in the future energy supply. This holds true even if a massive increase in opportunities for electricity import and export occurs. Indeed the installed power required ranges quite widely in the different scenarios: from a total of 290 GW up to nearly 540 GW. The lower value was calculated for the scenario targeting an 80 % decrease in energy-related CO_2 emissions and the upper value was calculated for the scenario with a 90 % decrease in energy-related CO_2 emissions, respectively.

3. As the share of fluctuating renewable energy sources continues to grow strongly, an increasing flexibility in electricity generation becomes just as necessary as a flexibly reacting electricity demand. Increased flexibility can become reality only if new applications for electricity use – over and above the conventional uses known today – are implemented. Such new applications are particularly important in the building and mobility sectors. At the same time, increased electricity use in these sectors implies that combustion systems (boilers, combustion engines) shall be gradually replaced by electric powered units (electric heat pumps, electric motors). These units convert the final energy (electricity) more efficiently into useful energy (heat, traction) than the fossil fuel based combustion processes used today.

4. All of the investigated scenarios foresee a rise in electricity generation and consumption due to a growing demand across all sectors. Depending on the scenario, values that are 20 % to 40 % higher than today are to be expected, despite the assumption made that due to efficiency increases, the electricity consumption of classical electric powered applications like lighting, mechanical drives, etc. will be reduced by 25 %.

5. A reduction of energy-related CO_2 emissions of at least 80 % below 1990 levels requires that fossil fuels, like gas or oil, be replaced more and more by renewable fuels. Accordingly the targets for CO_2 emission reductions cannot be achieved without the installation of large plants for producing synthetic energy carriers from renewable energy. Such systems would manufacture hydrogen, methane or liquid fuel using electricity generated from wind or solar PV. Here also, the total installed capacity of such systems varies widely among

the different scenarios: from less than 80 GW up to 180 GW. The lower value is for a scenario which assumes a large expansion in electric mobility. The upper value was calculated for the scenario targeting a 90 % reduction in CO_2 emissions compared to 1990 levels.

6. A dominant feature in the future energy system is the electrification of the heat supply. In almost all of the investigated scenarios, electric heat pumps are the main technology used to supply heat for single buildings. The percentage of electric heat pumps installed in the energy system increases with higher target values for CO_2 emission reductions. In all of the scenarios, solar thermal energy systems are to cover part of the low temperature heat demand in buildings and in industry.

7. In the scenarios that assume the rate of building renovations is much higher than today, a lower overall capacity of renewable energy converters for electricity generation is required. As a result, the total costs in these scenarios are lower than for the scenarios with more moderate renovation rates. In all of the investigated scenarios (except the scenario with a CO_2 emission reduction target of 90 %), the majority of the building stock is renovated to meet today's standards for new buildings and not to meet passive house standards.

8. An accelerated exit from coal-fired electricity generation by 2040 was shown to have a significantly positive influence on reaching the emission reduction targets successfully. In all scenarios with an accelerated exit, the calculated total costs for the energy transformation were lower than for the same scenarios with no accelerated exit. If coal-fired power plants are still in operation in 2050, then it will be very difficult to achieve more than an 80 % reduction in energy-related CO_2 emissions.

9. A tipping point is observed between the transformation pathways having 80 % and 90 % CO_2 emission reduction targets. In scenarios that target CO_2 emission reductions of 90 % only a very small amount of fossil fuels is available. Therefore, the energy systems in these scenarios require an appropriately large capacity of wind and solar PV to generate electricity, a large amount of installed storage as well as an appropriately large amount of plants that produce synthetic energy carriers. At the same time, the 90 % reduction target requires a more extensive energy renovation within the building stock. For single buildings that are not connected to a district heating grid, electric heat pumps will be almost exclusively installed for heat provision in this scenario.

10. During the occasional periods when the available renewable electricity is not able to meet the electricity demand, i.e. times of residual load, there must be enough complementary power plants available to supply power. These complementary power plants operate on fossil fuel, biogenic and synthetically manufactured energy carriers. Depending on the scenario, these plants consist of combined cycle power plants, combined heat and power (CHP) units as well as gas turbine power plants, in varying ratios.

The most important results concerning the costs of the energy transformation are:

1. For the case of stable fossil fuel prices up to 2050 and long-term low costs for CO_2 emissions (e.g. low trading prices for CO_2 certificates), simulations show that based on the least expensive scenario, the extra costs for transforming the energy system are approximately €1100 billion between 2015 and 2050. In this scenario, the transformation costs about 25 % more than continuing to

operate the present energy system as is up to 2050. Per year this is equivalent to about 0.8 % of Germany's gross domestic product (GDP) today.

2. The cost situation is dependent, of course, on the price development of fossil fuels and the costs levied on CO_2 emissions. If one assumes that fossil fuel prices increase annually by 3 %, then the cumulative total costs for transforming the energy system and achieving the targeted 85 % reductions in CO_2 emissions by 2050 are practically identical to the costs required to operate today's system as is up to 2050. A similar effect is achieved when one assumes constant prices for fossil fuels up to 2050 and a constant charging of costs of €100 per ton for CO_2 emissions.

3. After successfully completing the energy transformation scenario in which CO_2 emissions have been reduced by 80 to 85 percent, the total annual costs for the new system are no greater than the costs needed to operate today's energy system, i.e. €250 billion distributed over all end customers. This figure is valid based on today's prices for fossil fuels and today's trading costs for CO_2 emissions.

All costs stated here are based exclusively on the pure system costs. This means costs incurred from investments, their financing, the operation and maintenance of the systems and the purchase of fossil fuels and biogenic energy carriers, i.e. no external costs were included in the cost calculation.

From the macroeconomic perspective, the transformation of Germany's energy system demands a significant shift in cash flow, moving the cash spent on energy imports today to spend it instead on new investments in systems, their operation and maintenance. In this respect a transformed energy system requires a large expenditure for local added value, a factor which also does not appear in the shown cost analysis.

1 Introduction

In November 2012, we published the study »100 % Renewable Energies for Power and Heat in Germany« and in November 2013, the study »Energy System Germany – Model-based, Overall Investigation for the Long-term Reduction of Energy-related CO_2 Emissions through Energy Efficiency and the Use of Renewable Energies Considering All Sectors and Energy Carriers«. The simulation and optimisation model REMod-D (Renewable Energy Model – Germany) was the central tool used for the preparation of the studies. At this point in time, the model enables the cost optimisation of target systems of a German energy system taking into account a specified, permissible upper limit of energy-related CO_2 emissions. In the last two years, we have intensively worked on the further development of the REMod-D model. The most important modification is the possibility of mapping complete transformation pathways of system development from today until 2050 in detail and their optimisation by cost. This new study publishes the results of analyses carried out with the extended model.

1.1 Concept of the Study

The driving force of the energy transformation in Germany is the political goal of drastically reduced greenhouse gas emissions in order to limit the anthropogenic climate change and thus, any drastic influences on nature and the conditions of human life and economy. The declared political goal of the German Federal Government is to decrease the greenhouse gas (GHG) emissions by 2050 by at least 80 % [2], and wherever possible by 95 %, below 1990 levels [3, 4]. This objective is supported by a wide social consensus. The total amount of GHG emissions in the reference year 1990 amounted to 1,215 million tons of CO_2 equivalent (for this purpose, all greenhouse-relevant effects are converted into the climate-changing effect of CO_2 emissions). This value considered the CO_2 lowering in agriculture and forestry. For the years prior to 2050, reduction target values are defined as well: a reduction by 40 % by 2020, by 55 % by 2030, and by 70 % by 2040.

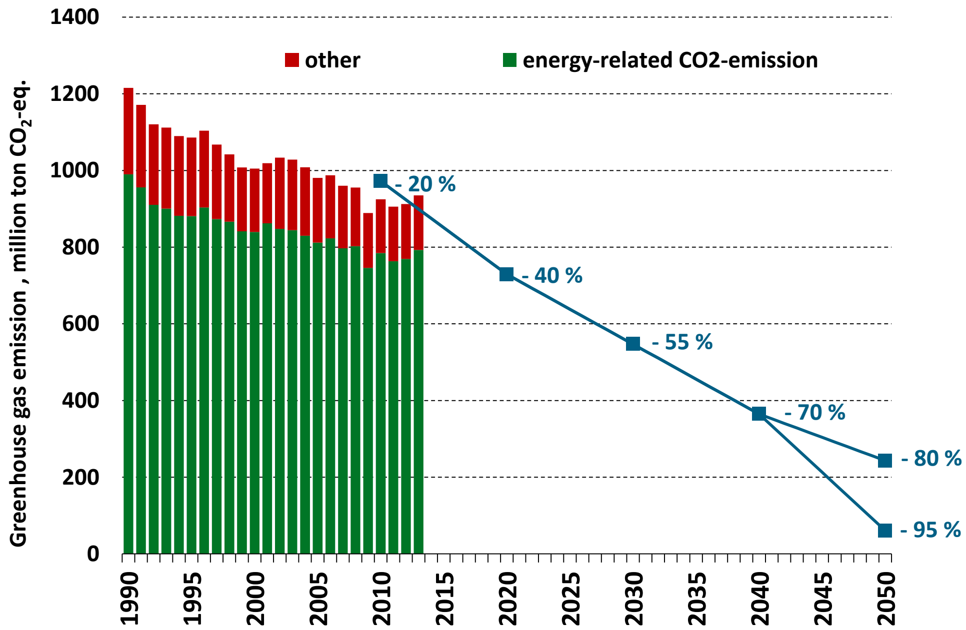


Fig. 2 Greenhouse gas (GHG) emissions in Germany from 1990 until 2013 and target values for the years up to 2050 (blue dots). The green bars represent the energy-related CO2 emissions and the red bars other GHG emissions (based on the data in [1]). The reduction values in percent refer to the reference value in 1990.

The value of the GHG emissions in the past is presented together with the mentioned target values for the period up to 2050 in Fig. 2.

The largest share of GHG emissions are energy-related CO_2 emissions with close to 990 million tons in 1990 and 793 million tons in 2013 (see green bars in Fig. 2). Thus, energy-related CO_2 emission may be at maximum 198 million tons in 2050 in order to achieve the reduction goal of 80 % compared to the reference year 1990. Here it is assumed that energy-related CO_2 emissions are reduced to the same extent as all other greenhouse gas emissions. A reduction by 95 % would mean a target value of 49 million tons. The relative portion of energy-related CO_2 emissions in the total greenhouse emissions has increased from around 80 % to 85 % in the period from 1990 to 2013.

On the one hand, the goal of our study is to investigate how a German energy system in line with the mentioned political goals could look like in 2050. On the other hand, the current study would like to answer the question, which transformation pathways would be feasible. The transformation costs should be analysed to identify the transformation pathways leading to the lowest transformation costs possible. To answer this question, we modelled the German energy system taking into account all important energy conversion techniques and considering all consumption sectors. We used this modelling to analyse the year-by-year development of the overall system. As main boundary condition, the target value of permissible CO_2 emissions must not be exceeded in any year – in other words, the system transforms itself following the climate path of virtue. Thus, our approach focuses on a temporally resolved hourly investigation of the interaction of energy provision and energy use across all sectors as well as on applying an optimisation to determine cost-optimised systems and/or transformation pathways.

Chapter 2 discusses the actual state of energy provision and use in Germany and describes the modelling methodology. In addition, the main assumptions and boundary conditions are presented. Chapter 3 presents selected results. At first, we analyze the system composition after transformation for different scenarios, followed by a detailed cost analysis. Chapter 4 investigates a selected system in detail and analyzes the energy balance in the investigated target year 2050.

1.2 Review of the 2012 and 2013 Studies

The focus of the study published in 2012 »100 % Renewable Energies for Power and Heat in Germany« [5] was on modelling and optimizing the power and heat supply. At that time, only these two sectors of the overall energy system were included in the REMod-D model (Regenerative Energy Model – Germany). The model allowed the optimisation of a target system assuming that no CO_2 emissions take place for the provision of power and heat in the target year (usually in 2050).

Next, the model was extended such that all consumption sectors, including mobility and industry, were considered in the modelling as well. At the same time, fossil energy carriers were considered in the modelling as well. Here, upper limits for the energy-related CO_2 emissions caused by the overall system were specified as boundary conditions for the optimisation. The optimisation goal was still a target system and not a transformation pathway. The results of different scenario calculations carried out with the extended model were included in the study »Energy System Germany – Model-based, Overall Investigation for the Long-term Reduction of Energy-related CO_2 Emissions through Energy Efficiency and the Use of Renewable Energies Considering All Sectors and Energy Carriers« [6] published in November 2013. A system configuration leading to an 80 % reduction of energy-related CO_2 emissions compared to the reference value in 1990 was presented in detail in the study. On the one hand, the most important results were data regarding the required quantity structure for the key components of a future energy system in line with climate protection – hence for wind turbines, solar panels, energy storage devices, energy renovations of buildings, and others – and, on the other hand, results regarding the yearly total costs of a future energy system. The result shows that, after transformation, a future energy system in line with climate protection leads to similar yearly total costs as our current system.

2 Initial situation and methodological approach

In this chapter, the initial situation of the German energy system is briefly presented based on the data of 2013 as well as the methodological approach. Here, all key assumptions and boundary conditions of the calculations are mentioned as well. All values of power conversion efficiencies, efficiency values, etc. of the used technologies as well as the specific costs can be found in the appendix.

2.1 Energy Consumption and Energy-related CO_2 Emissions in Germany

The primary energy supply in 2013 amounted to 3841 TWh [7]. As shown in Fig. 3, 262 TWh of it was used for non-energy-related applications, hence, for the chemical industry in particular. 3579 TWh were used for energy-related applications. The composition of energy carriers is shown in Fig. 3 as well. The portion of renewable energies in the primary energy supply that was used for energy-related applications was around 12 %, while the portion of fossil energy carriers was around 80 % and the portion of nuclear energy around 8 %.

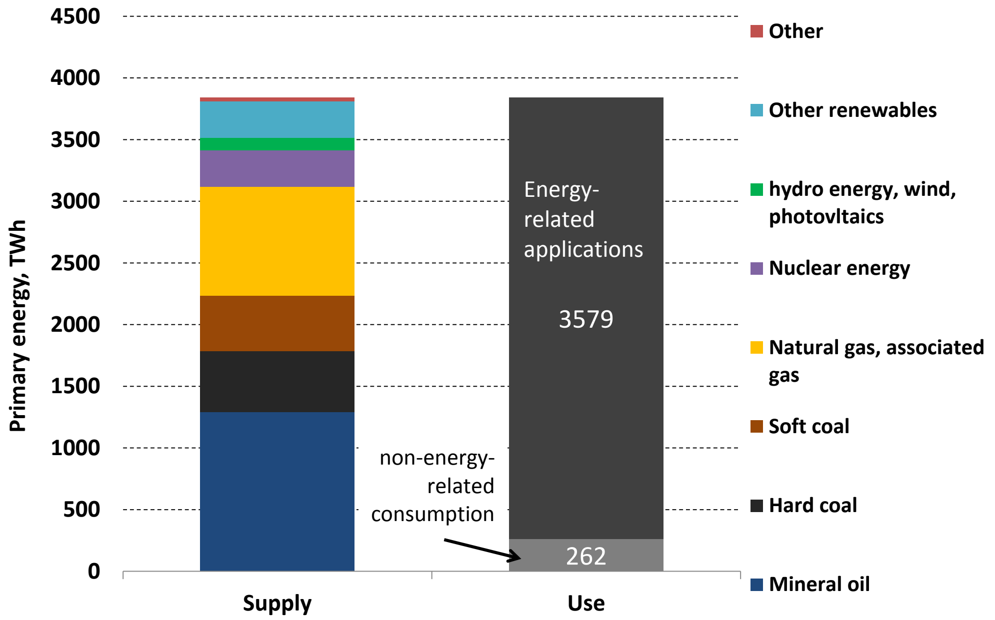


Fig. 3 Primary energy supply and usage in Germany in 2013 (own presentation using the data from [7])

Of the primary energy supply used for energy-related applications, 2575 TWh were supplied to various consumers as final energy. Own consumption as well as energy sector losses (including statistic differences) amounted to 1004 TWh (around 28 %). Final energy distribution to the consumption sectors industry, mobility, trade/commerce/services and households is shown in Fig. 4. Final energy is supplied to final consumers in the form of electricity, fuels, and district heat. The percentage of electricity in the final energy supplied amounts to 20 % (see right bar in Fig. 4). The final energy usage is distributed almost equally (around 28 % each) to the industry, mobility, and household sectors and to the trade/commerce/services sector (around 15 %). The relative portion of electricity in the final energy used is the highest in the industry sector and very small in the mobility sector. Electricity is mainly used in the area of rail-bound mobility (railway, public transportation), while fuels dominate in the areas of street-bound mobility, shipping, and aviation.

Figure Fig. 5 shows the final energy composition by application type. The right bar in the figure represents the respective portion of electricity in the final energy used for the different application types. Application types lighting, information and communication technologies (ICT), and cooling applications (air conditioning, process cooling) are characterized by a wide use of electricity as final energy. However, in the area of heat applications (space heating, hot water, process heat), electricity is of secondary importance. The application as »mechanical energy« is currently dominated by fuels as well, as the large mobility is included in this application type. Electricity application in the »mechanical energy« application type mainly refers to pumps, conveying systems, and drives.

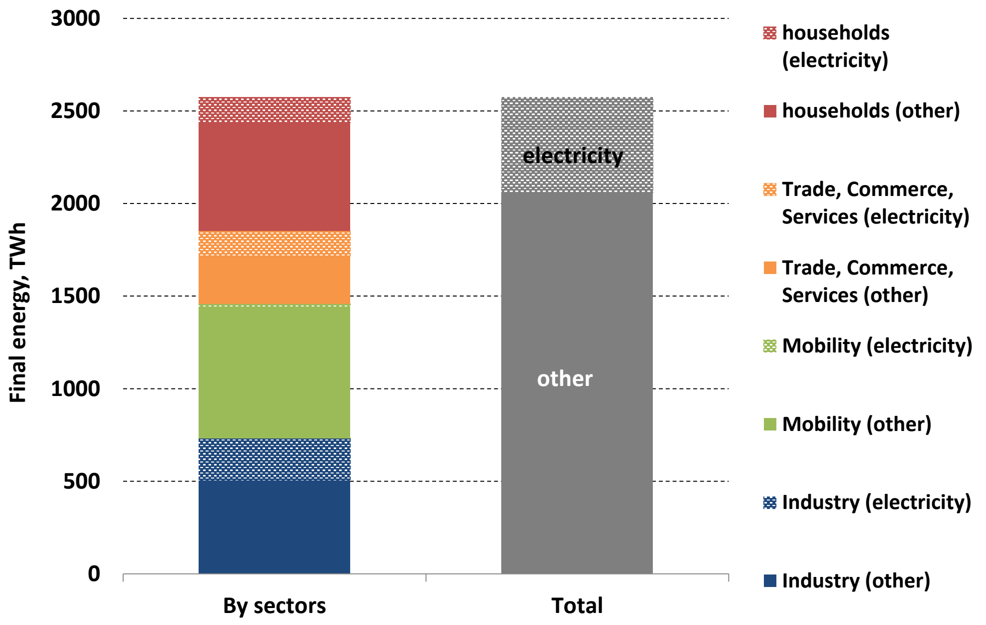


Fig. 4 Composition of final energy usage by consumption sectors for Germany in 2013 (own presentation using data from [7])
Electricity: electricity final energy
Others: other final energy carrier (fuels, district heat)

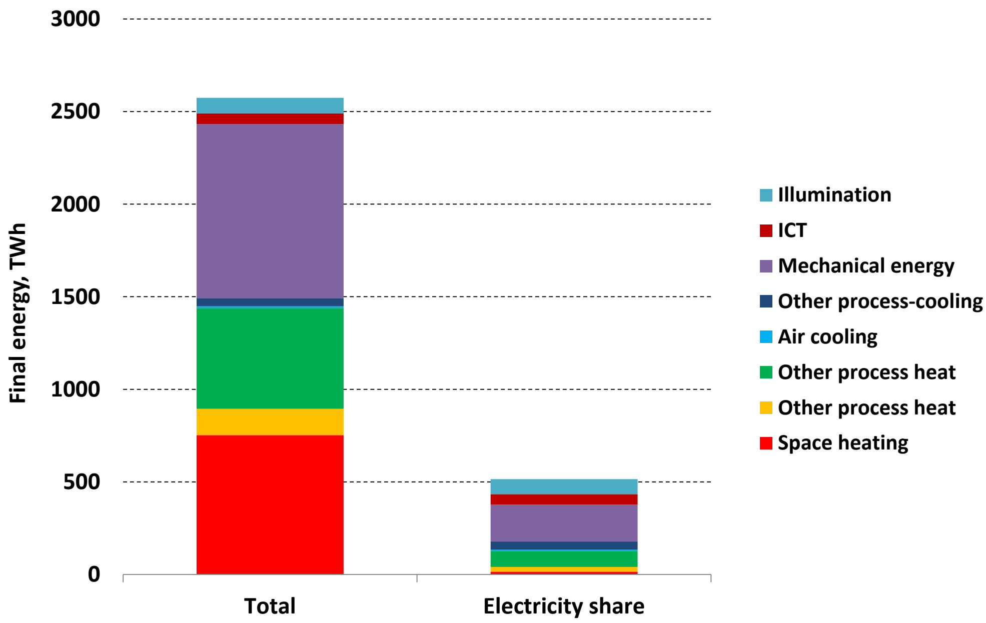


Fig. 5 Composition of final energy by application type for Germany in 2013 (own presentation using data from [7])
(ICT: information and communication technologies)

Fig. 6 shows the final energy used in a modified breakdown. Here, we compiled the data from [7] in a different form for better comparability of our results (see results in section 4.4). In this presentation, the final energy amounts were assigned to the following modified fields of application:

- Low temperature heat – hence, space heating and hot water – in buildings (residential buildings as well as commercial and industrial buildings) (in Fig. 6 referred to as »Heat for building«),
- Other process heat, hence, in particular, process heat in trade and industry (referred to as »Other process heat«),
- Mobility (referred to as »Mobility«), and
- Applications that are currently mainly or completely covered by electricity, i.e., lighting, air conditioning and refrigeration, ICT, and electricity-based railway traffic (referred to as »Classic electricity applications«)

This breakdown highlights that electricity is currently only used to a very small extent as final energy in the fields of application »Mobility« (round 2 % of the final energy used in this field of application) and »Heat for building« (4 %). For the field of application »Other process heat«, the electricity portion amounts to 16 %. In the case of classic electricity applications, however, electricity is used dominantly (91 %) in this field of final energy application. Merely a few cooling applications use fuels or heat (e.g., in absorption cooling systems).

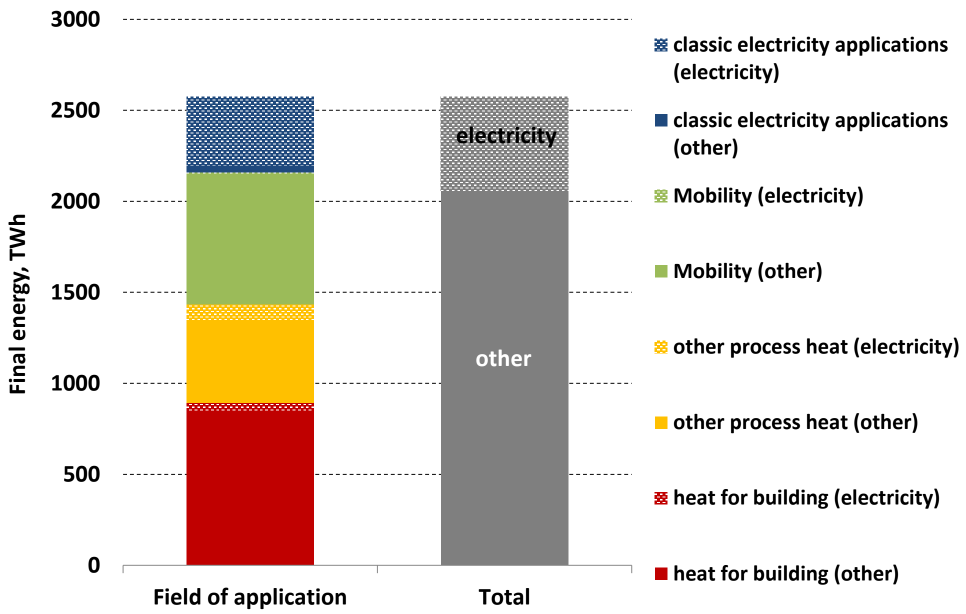


Fig. 6 Composition of final energy usage by modified fields of application for Germany in 2013 (own presentation using data from [7])
(Electricity: Electricity final energy
Others: Other final energy carrier (fuels, district heat)

The energy-related CO_2 emissions in Germany in 2013 amounted to around 793 million tons. With that, they represent close to 85 % of the overall GHG emissions [1]. The composition of the emission origin by different sectors is shown in Fig. 7. Here, the sector distribution in the data of the German Federal Environmental Agency (UBA) does not match the distribution used in the energy data of the German Federal Ministry for Economic Affairs and Energy (BMWi). The largest individual portion of energy-related CO_2 emissions with close to 45 % is caused by electricity generation. Although electricity amounts to around 20 % of the final energy, its portion in CO_2 emissions is significantly larger due to high losses and own consumption in the power plant sector. Mobility is responsible for around 20 % of the energy-related CO_2 emissions with street traffic representing the largest portion. Around 18 % are caused by business, public sector, and households. Here, fuels for space heating and hot water play the largest role. The CO_2 emissions caused by electricity requirements of these sectors are included in this chart in the electricity generation emissions. Additional 16 % are caused by the manufacturing and construction industry. The CO_2 emissions of the electricity drawn by these sectors are also included in the values of electricity generation. Thus, these emissions are mainly caused by fuels used for industrial processes.

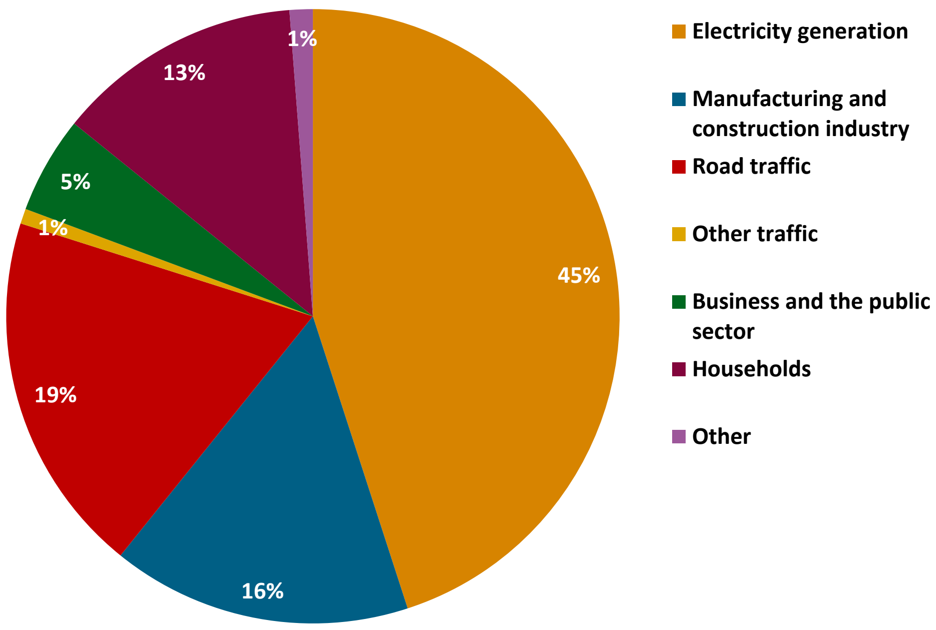


Fig. 7 Composition of energy-related CO_2 emissions in Germany in 2013 (own presentation using data from [1])

2.2 Basic Approach: Assumptions and Boundary Conditions

First, we explain the basic methodological approach used to answer the main question of this study adequately: the question regarding a cost-optimal transformation of the German energy system taking into account all energy carriers and consumption sectors, which can be used to meet the entirety of the decided climate protection targets along the timeline. Briefly explained, we selected the following approach:

- We simulate the overall German energy system hour by hour, taking into account a variety of energy carriers, converters, and storage, as well as the electricity (intrinsic electricity applications), heat, mobility, and industrial process heat consumption sectors. Due to the complexity of the system, several simplifications and high aggregation of individual consumers are applied. Modelling starts on January 1st, 2014 and ends on December 31st, 2050. All energy requirements of all consumers must be covered in every hour. The energy balance must be fulfilled and security of supply must be ensured.

- The system composition can change every year. Here, it is differentiated between expansion and replacement. For example, wind turbines can be added so that more wind turbines will be installed at the end of the year than at the beginning. The same applies to many other system components (converters, storage). At the same time, old systems that reached their service life must be replaced. Or they are removed without replacement as this is more cost-effective from a system point of view. In the case of other system components, such as heat supply systems and motor vehicles, the number of systems or units is externally specified. For example, the exact number of required heating systems must ensure that all buildings are sufficiently supplied with heat. However, it does not make sense to install more systems. The composition of technologies used can changed within the scope of system optimisation. For example, if 800,000 heating systems are removed in a year due to age reasons, they can be replaced by similar or different systems. This composition and its chronological development are an optimisation result, similar to, e.g., the decision regarding the addition of wind turbines or the extent of energy-related renovation measures in existing buildings.

- We selected the cumulative total costs for the energy supply from 2014 until 2050 as target function for the development optimisation of the overall system. The following costs items are included in these costs: investments for expansion, conversion, and replacement of system components, financing costs for investment financing, operating and maintenance costs for all systems, and the costs for fossil and biogenic energy resources. However, we did consider that a system that was not converted also required investments. Such investments were respectively deducted again. To give an example: if a gas boiler in a building is replaced due to age reasons, the reference case would be to install a similar gas boiler. If a heat pump would be installed instead in our simulation, this would require a higher investment. For this reason, the difference costs between heat pump and gas boiler were inputted only during costing in order to record the added costs of the optimised system in line with climate protection compared to a non-changing reference system. The same approach was applied to motor vehicles. The respectively added costs of a novel vehicle concept compared to the reference technology – combustion engine with fossil fuel – were studied only. In the cost analysis, this approach means that the determined costs of the system in line with climate protection can be directly compared to the costs of the reference system. Here, it must be considered that the reference system also requires replacement investments, as old systems must be replaced with similar new systems at the end of their service life.

- To identify cost-effective transformation pathways, many simulation runs are performed with different system compositions and/or development pathways of the system compositions. Using an optimizer, the pathways are successively determined, where the target function, i.e., the cumulative total costs, assumes minimum values. The result is a cost-minimal variant. Due to the nonlinearity of the problem, it cannot be ensured that this variant is the absolute minimum in the high-dimensional parameter space (with up to 2,000 independent variables). The solution space features different solutions – transformation development pathways – resulting in relatively similar cumulative total costs.

The detailed functionality of the model, important boundary conditions, and the target function defined for optimisation are presented in the following chapters.

2.2.1 Simulation Model and Management

As explained above, the REMod-D-TRANS simulation and optimisation model is used to calculate the transformation of the current German energy system into a target system in 2050. It is based on an extended version of the REMod-D model [8].

The basic functionality of the REMod-D model is based on a cost-based optimisation of a German energy supply system, whose energy-related CO_2 emissions do not exceed a specified target value and/or target pathway. The optimisation target is to dimension all generators, converters, and consumers at minimum costs such that the energy balance of the overall system is met in every hour.

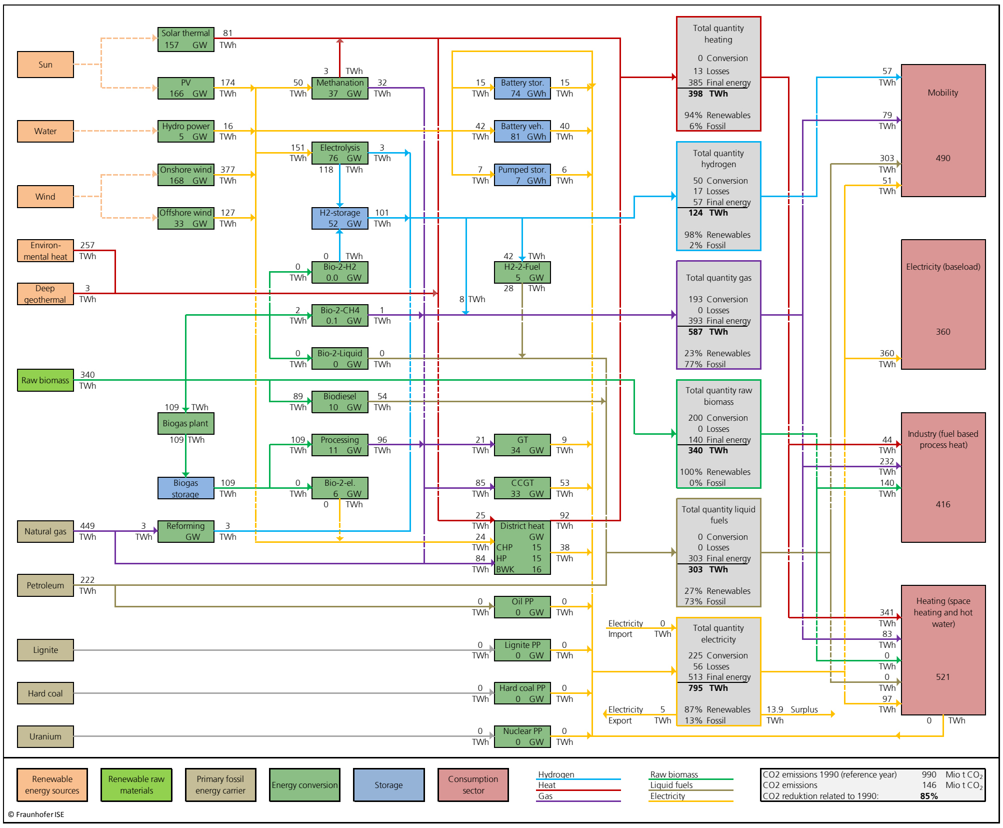


Fig. 8 Scheme of the energy system as presented in the REMod-D simulation model. The illustration shows all conversion pathways of fossil primary energy and/or renewable energies up to the respective consumption sector. (Values are examples for the scenario presented in detail in chapter 4 with a reduction of energy-related CO_2 emissions by 85 %)

Conventional power plants with lignite and hard coal as fuel, nuclear power plants, oil-fired power plants, gas turbines, CHP plants, and gas-fired and steam power plants are implemented as generators. Renewable energy can be generated in the model using wind turbines onshore and offshore, photovoltaic systems and hydropower plants. Biomass can be used in different usage pathways either directly or after conversion into a different energy carrier. For example, wood can be used in boilers in order to provide process heat for industrial applications and for the generation of low-temperature heat in the building sector. Biogas systems, gasification systems with subsequent synthetisation into hydrogen, methane, or liquid fuels and biodiesel systems are implemented as systems for the conversion of biomass. Electrical energy storage systems in the form of stationary and mobile (in vehicles) batteries or pumped-storage power plants are used as storage systems. Hydrogen storage systems and thermal hot water storage systems in different orders of magnitudes are considered in addition. With respect to methane storage system, the simplified assumption is made that currently already existing storage capacities (including grid, approx. 210 TWh [9]) will also be available to the system in the future. Thus, they are not considered in the optimisation. [8]

The energy demand side is divided into four groups according to the modified fields of application introduced in section 2.1: Mobility, intrinsic electricity applications, heat for buildings (residential buildings, as well as non-residential buildings and industrial buildings), and process heat in the industry. The mobility sector is mapped in detail through passenger cars and trucks with seven vehicle concepts each. The energy demand of aviation, shipping, and fuel-based railway traffic is considered in the balance, however, not temporally resolved. The basic electricity load is mapped using load profiles based on the data of European transmission grid operators that was reduced by the current load for heating systems. This load is calculated model-endogenously and is not included in the basic load. [8]

The building sector is implemented with 18 possible heat supply technologies. Each of these heating technologies can be optionally supplemented with a heat storage device or solar thermal energy system. Fig. 9 shows an example of the »electrical brine heat pump« system, hence, a brine-water heat pump with ground as heat source. The possible energy flows between the individual system components are shown. Thermal storage devices can be charged through solar thermal energy, as well as through heat from excess power (directly or via the heat pump). The latter option allows the flexible use of power in the case of a negative residual load. Vice versa, the heat pump can be switched off and the heat storage discharged in the case of a positive residual load and simultaneous heat requirement.

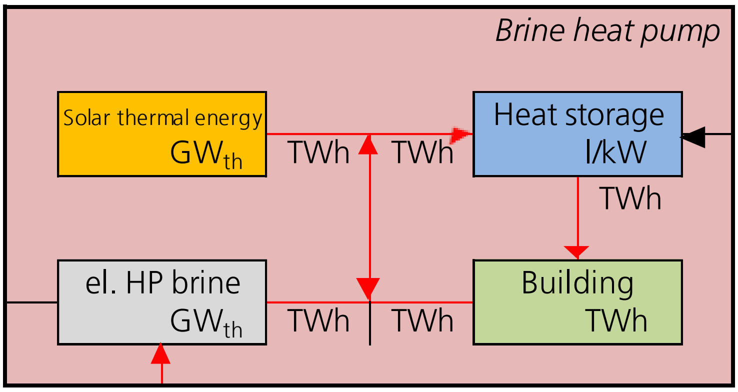


Fig. 9 Schematic design of the heating systems on the example of a ground-coupled, electrical heat pump (red lines = heat, black line = power). (HP: heat pump)

The energy demand of the industry is derived from the statistical data of the German Federal Ministry of the Economy [7] and refers to the fuel-based energy supply for process heat. The electricity demand of the industry is included in the basic electricity load. Fig. 8 shows the schematic presentation of the energy system mapped in the REMod-D model. The details of the usage side (e.g., the variety of heating systems, drive concepts for vehicles) are not included in the presentation. [8]

The REMod-D model is based on simple physical models of all components contained. The central component is the energy exchange across the electricity system. A load still to be covered after feed-in of renewable energy is compensated by the generation of electricity from systems of different sectors. Excess electricity, on the other hand, can be stored and/or converted into different electricity forms (chemical and thermal) and is thus accessible for all sectors. The operation of electricity-generating and electricity-using systems in the case of positive and/or negative residual load follows a defined management strategy. The component usage sequence in this management strategy follows the path of highest energy efficiency at simultaneously lowest CO_2 emissions. Fig. 10 shows the different stages for the generation and usage of electricity in the case of a positive and/or negative residual load in the system. To cover positive residual loads, CHP plants are operated first after the use of electrical storage systems and biogas CHP. The generated heat is then used to charge heat storage devices and/or to cover thermal loads if these are present at the same time. Any additional demand is covered by the operation of combined cycle gas turbine (CCGT) plants and CHP plants in »electricity only mode«. The remaining load is covered by highly flexible gas and oil turbines and with the help of the remaining, flexibly usable power of conventional lignite and hard coal power plants. In model calculations that also investigated the electricity import, it can also contribute to covering the electricity demand at the end of the usage cascade with a previously defined maximum power. [8]

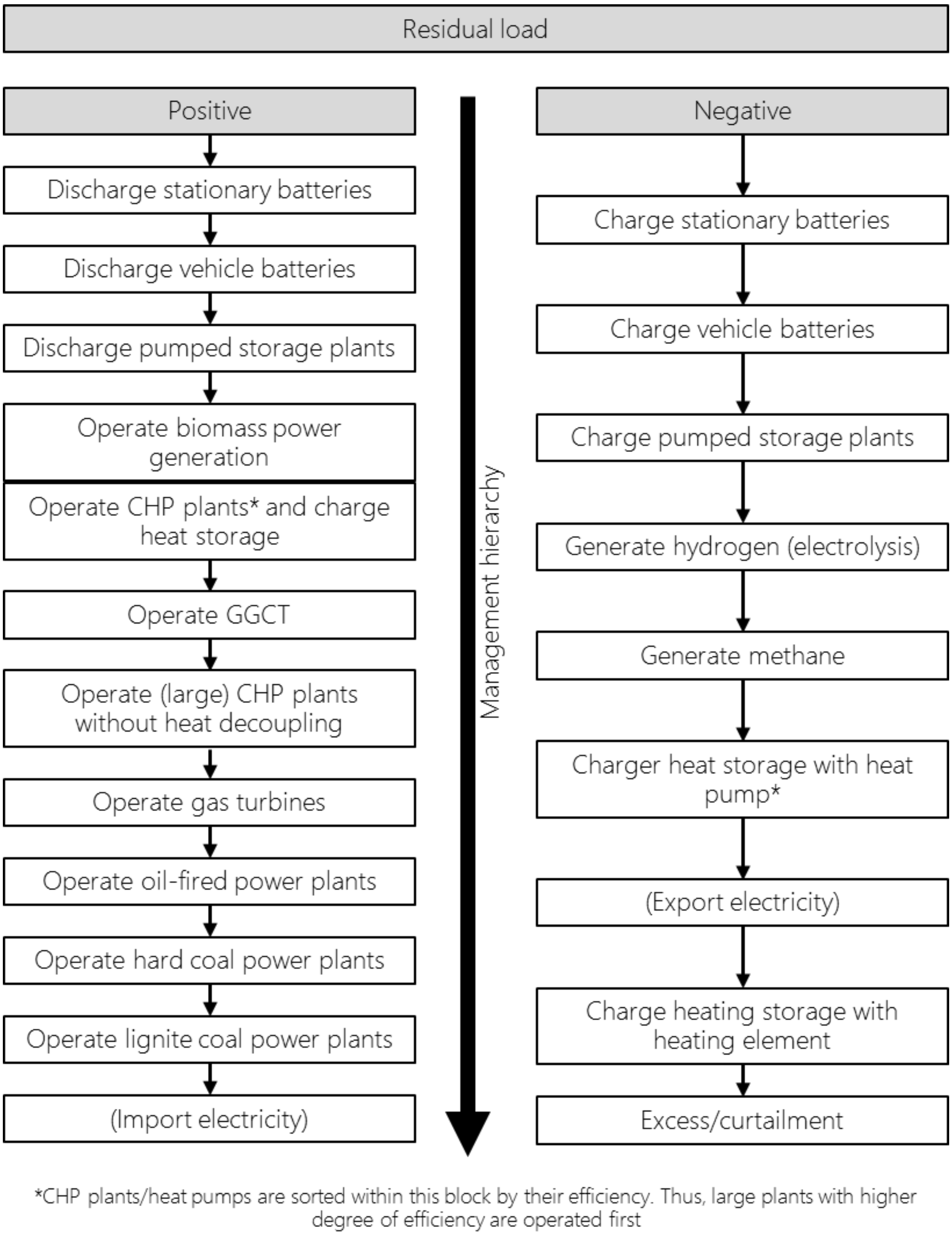


Fig. 10 Management sequence in the case of positive (left) and negative (right) residual load. Source: [8]

The weather influence is decisive for the different residual load states during the simulation. To map this influence adequately, three real data records of 2011-2013 are used within the scope of calculation. The weather data used in the model for the calculation of feed-in and load profiles are based on publicly accessible data of the

German Meteorological Service [10, 11]. The weather data from two different reference locations in Germany, Braunschweig for North Germany and Würzburg for South Germany, are processed in the model. Hourly outside temperature values and emission data are used from both locations. To consider the stochastic effects, the available weather years of 2011, 2012, and 2013 are randomly distributed to the period from 2014 to 2050 at the beginning of the calculation for the weather calculation in the investigated period from 2014 to 2050. Every iterative calculation of a transformation pathway within an optimisation uses this sequence always in the same form. This way, a consistent data record was generated for the entire period from 2014 to 2050, which is used as basis for the electricity generation from solar energy and wind, which is used for calculation of the heating load of the building sector, and which is used as the basis for the heat generation from solar thermal energy systems. The real profile of the power consumption data of these years is also used in the same sequence to ensure an adequate correlation between the profile of the basic electricity load and the profile of the power provision from renewable sources, which is defined by the profile of the meteorological variables. [8]

2.2.2 Cost assumptions and target function

The technology specific system costs are obtained from an exogenously specified cost function depending on the investigated year. When determining this cost function, the values of every technology given in table 3 in appendix 1 for start year 2015 and target year 2050 were used as start and end value. Respectively, different data sources were used for this purpose. These are indicated in table 3 in appendix 1, respectively.
The curve profile of the specific costs of photovoltaic systems is presented in figure 4 as example. The curve profile is based on studies discussing the cost degression behaviour of the respective technologies. As result, a specific cost value in $€_{2013}$/kW is available to the model for every year.

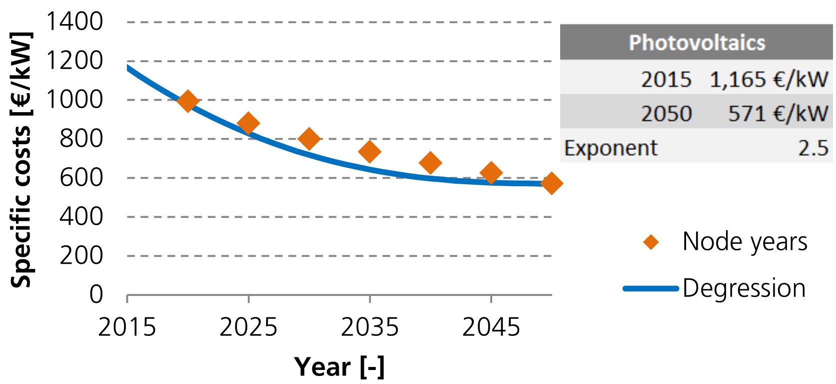


Fig. 11 Cost profile of photovoltaic systems up to 2050. Source: [8] Based on [12].

In addition to the cost investigations for components, such as converters or storage devices, where the specific costs are used relative to the thermal or electric power and/or capacity of the systems, costs for energy saving measures in the building sector through energy renovations are considered as well in the model. Here, energy-related additional renovation costs are considered only that result from the difference of the full costs and the costs incurred for renovations for standard building preservation. This is based on the so-called coupling principle, which states that an energy renovation of a component is only performed if the component is to be renovated anyway (see [13]; [14]; [15]). Two energetic standards are assumed for energetically renovated buildings in the modelling. These are referred to as »fully renovated« and »highly efficient«. Based on the renovation levels [16] defined in the »Climate-neutral Building Stock 2050« project, »fully renovated« complies with the standards of the Energy Saving

Regulation (EnEV) 2009, however, tightened by 25 % (EnEV -25 %), and »highly-efficient« complies with the requirements on a passive house based on [17].

Similar to the approach for energetic building renovations, the coupling principle is also applied in the mobility and heating technology sectors. Here, passenger cars with classic combustion engine and heating technologies with gas condensing boiler are assumed as reference technologies for the costs required for system renovation. Thus, the financial additional effort of the changed energy system relative to the current system is considered in the total costs of the investigated climate protection scenario.

The calculation of the total costs required over the investigation period (2015-2050) for the transformation of the energy system (fuel costs, investments and expenditures for maintenance and operation, financing) follows the specification of VDI Directive 2067 and annualised for every year[1]. The reference period for the annualisation is the respective technical service life of the technologies. Interests are specified per technology. Here, two interest rates are used consistently: 4 % for investments mainly by private investors (e.g., house owners and motor vehicle owners) and 7 % for investments by institutional investors, hence mainly investments in power plants, wind turbines, and infrastructure facilities.

The target function *Z* of the optimisation for the investigation period from 2015 to 2050 with *N* technologies results, according to the following equation, from the sum of annualised asset- and operation-bound costs of all technologies and the incurred total fuel costs for every year [8]:

$$Z = \sum_{t=2015}^{2050} \sum_{i=1}^{N} A_{0_{i,t}} \frac{q_i^T (q_i - 1)}{q_i^T - 1} (1 + f_{O\&M_i} \cdot \frac{T}{q_i}) + B_t$$

With:

$A_{0_{i,t}}$	Investments in technology *i* in year *t*
$A_{i,t}$	Total annuity of technology *i* in year *t*
$A_{k_{i,t}}$	Annuity of asset-bound costs of technology *i* in year *t*
$A_{b_{i,t}}$	Annuity of operation-bound costs of technology *i* in year *t*
$f_{O\&M_i}$	Factor of maintenance and service costs of technology *i*
q_i	Interest factor (corresponds to 1 + interest rate in %) of technology *i*
T	Investigation period
B_t	Fuel costs in year *t*
N	Total number of all technologies

In contrast to cost calculation according to VDI Directive 2067, reinvestments are defined by the optimisation in the case of costing for transformation pathways. If the technical service life of a system ends, it is decided as optimisation result, whether this system will be replaced in the respective year with a system of the same type or a system of a different type. An assessment of the future of investments can be specified exogenously in the form of a discounting rate equal for all technologies. The reference year is 2013. Based on [18], a real discounting rate of 3 % is assumed consistently in the optimisation calculations presented here.

[1] All cost values are converted into $€_{2013}$. Furthermore, it is simplified and assumed that the price-increase rate of maintenance and operating costs is identical to the assumed rate of inflation (here: 1.7 %).

2.2.3 Boundary conditions and general assumptions

Due to the high complexity, mapping the German energy system into a model requires different assumptions and simplifications. For example, developments not subject to optimisation are specified for the model exogenously. To the extent possible, the respectively required assumptions are based on the results of other studies accessible in scientific publications, respectively. The decisive assumptions are presented in the following for better interpretability of the results:

- Driving boundary condition for the calculation of the transformation pathways is the maximum permissible amount of energy-related CO_2 emissions in every year.

- The maximum possible addition of implemented technologies is limited through maximum specified year-by-year expansion quantities. This should consider that it is not possible to build and install an unlimited number of systems, e.g. wind turbines, due to production limitations. The assumed »guidelines« of the respective technologies can be obtained from table 4 in the appendix. These numbers were based on current market numbers. Market numbers for technologies that cannot have a significant current market share were determined as follows: First, the maximum potential limit of the technology in 2050 was determined in the literature. Next, the year-by-year upper limits were selected such that the sum of upper limits corresponds to the determined maximum potential limits in 2050.

- Technical potentials for solar and wind. Based on the GHG-neutral Germany 2050 study [19], it is assumed here that 45 GW_{el} and/or 189 GW_{el} onshore and/or offshore wind turbines are possible and that approx. 300 GW_{el} photovoltaic systems (including approx. 25 GW_{el} open spaces) can be installed.

- It is assumed that the number of buildings in Germany increases from currently approx. 25.4 million to 26.9 million in 2050 [20]; [21]. It is additionally assumed that every newly built building corresponds at least to the previously defined »fully renovated« renovation status.

- The number of passenger cars in the mobility sector decreases slightly from currently approx. 47.8 million to approx. 45 million in 2050. However, the number of trucks increases slightly from 5.1 to 5.4 million in 2050 (own assumptions based on [22]).

- The energy demand of aviation and shipping in Germany is assumed to be consistent at the current level. It is additionally assumed that liquid fuels only are considered as energy carriers.

- It is assumed that the energy demand for industrial processes currently operated directly with fuels reduced by 10 % from currently close to 458 TWh [7] to 414 TWh in 2050. A conversion efficiency of 90 % from final to useful energy is assumed in the model. Industrial process heat is considered in the model as constant hourly load.

- The basic electricity load based on the time series of the European transmission grid operators (see [23]) contains any electricity currently demanded in Germany minus the electricity for space heating and hot water with hourly resolution. Electricity for space heating and hot water is calculated model-endogenously and the basic electricity load corrected, respectively. The electricity demand contains, e.g., electricity for electrical railway traffic, households, industrial processes, lighting, air conditioning, cooling, etc. In total, the result is a yearly electricity demand of the system of approx. 500 TWh in start year 2013 [7]. Within the scope of the transformation calculations, this current electricity demand is reduced by 25 % by 2050 in line with the goals of the German Federal Government[1]. The reduction is linear over the investigation period.

- Conventional lignite and hard coal condensing power plants and oil-fired power plants are initially recorded with plant-specific age and installed power using the so-called power plant list [24] for 2015. In the course of the investigation period, the installed power of these power plants reduces after expiration of the respective technical service life. Table 5 in the appendix illustrates the dismantling profile of these power plants. Thus, it is not possible in the model to replace these power plants with power plants of the same type. They are not included in the optimisation. Depending on the investigated scenario, an early exit from coal power plants is investigated (see section 2.3).

- Gas-fired and combined cycle power plants (CCGT) are recorded at the beginning of the calculation analogously to the power plants mentioned above. However, within the scope of optimisation, there is the additional possibility to further expand the installed power of these power plants.

- Electricity feed-in from hydropower plants is mapped with hourly resolution based on the data of EEX-Transparency [25]. The installed power of today's power plants is assumed to be constant throughout the investigated period. Thus, the installed power of these power plants is not optimised.

- Pumped storage plants are not included in the optimisation. Bases on current values of an installed power of approx. 6.3 GW, and storage capacity of approx. 40 GWh, [26, 27] an increase to 8.6 GW and/or 70 GWh is assumed until 2050 for the dimensions of these plants (power and electric storage capacity) (own assumptions based on [28]).

- The import and export capacity of the German energy systems is assumed to be maximum 5 GW_{el} in most calculations. This corresponds to approx. one third of the currently available capacity of approx. 17 GW_{el} [29]. We consciously decided to keep this value comparatively small. The target of this approach is the investigation of the German energy system as independently as possible from compensation deliveries of adjacent countries. Section 4.5 investigates the influences of an increased electricity exchange capacity with adjacent countries on the system development in more detail for a selected scenario.

- The biomass available to the system, divided by wood and wood-type biomass, organic waste, and cultivated biomass, is assumed to be a summary target value of up to 335 TWh. [30]

- Solar process heat can partly cover the process heat for industrial processes. Assuming that up to 10 % of industrial process heat is covered in 2050 by using solar thermal plants, a maximum expansion of 0.5 % per year is defined

[1] http://www.bundesregierung.de/Webs/Breg/DE/Themen/Energiewende/Fragen-Antworten/1_Allgemeines/1_warum/_node.html

as upper limit. The optimisation algorithm determines the amount of solar process heat in the system.

- For oil-fired boilers it was assumed that they cannot be replaced with another oil-fired boiler after expiration of their technical service life. The upper limit of the optimisation for these technologies is thus set to zero for the investigation period.

- The portion of buildings with district heat connection is limited in the model to a maximum value of 25 % in 2050. In comparison: district heat connections represent currently approx. 14 % of all heat supply installations.

2.2.4 Remark Regarding Result Accuracy

It is obvious that mapping a very complex system (such as the energy system) is only possible with simplifications. This includes in particular spatial aggregation – the entire system is summarised in a spatial node – and the aggregation of similar system components. Due to spatial aggregation, spatial compensation effects are neglected. Spatial aggregation effects can be of attenuating nature, as extreme results do not occur everywhere at the same time. Thus, a rather unfavourable situation is mapped here using the selected approach. However, due to spatial aggregation, it is assumed at the same time that excess energy at one location can be used at the same time at a different location. Thus, restrictions caused by limited grid capacities are neglected. It is difficult to provide a solid estimate of the introduced error compared to reality using such assumptions. However, for not considering grid restrictions in the physical model: we have tried to compensate this by making assumptions regarding the required expansion of electricity grids depending in the expansion of renewable energies. A grid expansion is assumed, which is very close to the »copperplate« model approach. Costs are included in total costing, respectively.

With respect to cost information, the largest uncertainty is that cost projections must be made for all components included in the system to determine the year-by-year costs for investments. We have tried to provide solid cost development estimates for all components. For components, for which the cost projections in different sources were very different, we assumed average values. Should the costs for all elements (decisively contributing to the total costs) develop significantly differently than assumed, this would have respective influences on the result. However, statements regarding cross-comparisons between different investigated scenarios are only affected in second order, as such errors in the cost projections would affect all scenarios.

Overall, we are not familiar with any analyses that investigated the system and cost development for all consumption sectors and energy carriers of the energy system transformation to a similar level of detail, based on a model approach, which studies the energy flows in the system on an hourly basis so that security of supply is ensured for all consumers not only arithmetically, but also at any point in time. Based on this and despite the uncertainties mentioned above, the results seem to provide a plausible and solid cost analysis for the transformation of the German energy system that goes beyond any data and statements previously available.

2.3 Investigated Climate Protection Scenarios

If all sectors and energy carriers are investigated in all of their development possibilities, a vast variety of options exists in the development of the German energy system in line with the politically targeted climate projection objectives. However, several central elements can be identified, which decisively influence the transformation process and, thus, must be investigated in detail in different scenarios. This concerns the following elements: pathway and target value for the reduction in CO_2 emissions, development of energy renovations of the building sector, development of the mobility sector, and the usage duration of coal as energy carrier in the sector of thermal power plants. The investigated developments of these elements are briefly explained in the following sections. An overview of all investigated scenarios is provided next.

2.3.1 Target Reduction Value for Energy-Related CO_2 Emissions

According to the presentation in Fig. 2, the higher-priority long-term target of the climate protection policy of the German Federal Government is the reduction of greenhouse gas emissions in Germany by at least 80 % by 2050 compared to the reference value in 1990. We have defined this value as target value for the reduction of energy-related CO_2 emissions in most of our scenarios. However, there are studies that suggest that a reduction of energy-related CO_2 emissions must be greater than 80 %, as in other areas, such as agriculture, such a high reduction is not realistically feasible. In this respect, we have studied additional scenarios, in which energy-related CO_2 emissions are reduced by 85 % and 90 % by 2050 compared to the reference value. The respective trajectories that represent the boundary condition for the respective scenario calculations are shown in Fig. 12.

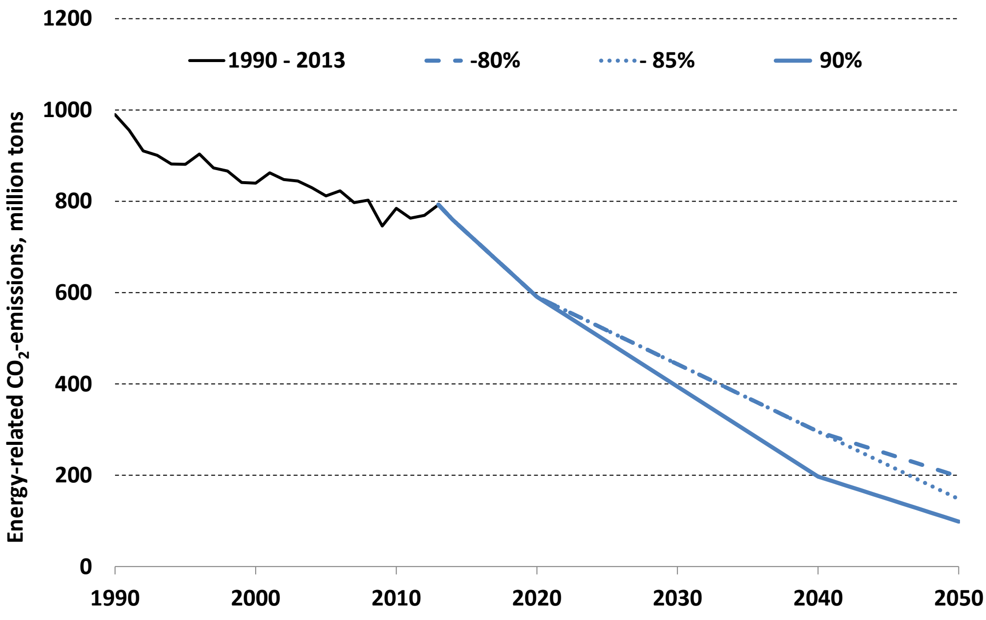


Fig. 12 Development of energy-related CO_2 emissions in Germany from 1990 to 2013 and the upper limits used between 2013 and 2050 in the investigated scenario variants. ([8], [1])

For a reduction by 85 %, a higher reduction was merely assumed in the decade of 2040 to 2050 (see, e.g., [21]). For a reduction by 90 % by 2050, a higher reduction was already assumed starting from 2020. The result is a reduction by 80 % already in 2040.

2.3.2 Energy Renovation of the Building Sector

The energy renovation of the building sector is one of the most important elements within the scope of the climate protection policy of the German Federal Government. The better the structural thermal insulation of all buildings, the less energy is required for space heating, and thus, the less energy must be provided by the overall system for space heating. However, the costs involved with energy renovations must be considered in the context of transformation optimisation of the overall system.

Within the scope of our modelling, we have investigated two different scenarios:

- Low increase in the renovation rate (referred to as »low«): in this scenario it is assumed that the renovation rate increases slightly only compared to today from round 200,000 renovation cases per year to 250,000 renovation cases per year.
- Ambitious increase in the renovation rate (referred to as »ambitious«): in this scenario it is assumed that the renovation rate increases significantly to at least 600,000 renovation cases per year.

The number of building renovated to a high (referred to as »fully renovated«) and/or very high (»highly efficient«) energy standard is the result of the respective optimisation. It is assumed that new constructions must at least meet the »fully renovated« energy standard.

2.3.3 Mobility Sector Development

In addition to the currently dominating combustion engines with classic fuel mix (gasoline, diesel) for operating motor vehicles, different drive concepts are feasible in the future. These options include vehicles with combustion engine with gaseous fuel, vehicles with batteries and electric motor, as well as vehicles with fuel cell and electric motor. In addition, mixed forms such as vehicles with combustion engine and additional battery with electric motor (plug-in hybrids) are possible as well. As the development of the vehicle sector depends on many factors and forecasting is difficult, we have differentiated between five scenarios:

- »Classic«: no significant change in the composition of the vehicle sector: here it is assumed that combustion engines with classic fuel mix will continue to dominate the area of motorized individual mobility as well as the area of freight transportation. (Short name of the scenario: »classic«)
- »CH4«: dominant portion of vehicles on methane (and/or natural gas) basis: here it is assumed that vehicle with combustion engine dominate, which use gaseous fuel distributed via the existing natural gas network. This fuel is a mix of fossil natural gas, refined biogas, and methane gained from renewable electricity. The composition – i.e., the share of each component in the mix – is the result of the respective system optimisation. (Short name of the scenario: »CH4«)
- »H2«: dominant portion of vehicles on hydrogen basis: here it is assumed that a large portion of the vehicle sector is operated with hydrogen from renewable electricity, which is converted into electricity in fuel cells to drive an electric motor. (Short name of the scenario: »H2«)
- »Electric«: massive increase in vehicles with electric drive: here it is assumed that in 2050 passenger cars with purely electric drive are sold only and that half of the street-bound freight transport is realised with electric drive. (Short name of the scenario: »electric«)
- »Mix«: In this scenario it is assumed that a mix of all the technologies mentioned above is used. (Short name of the scenario: »mix«)

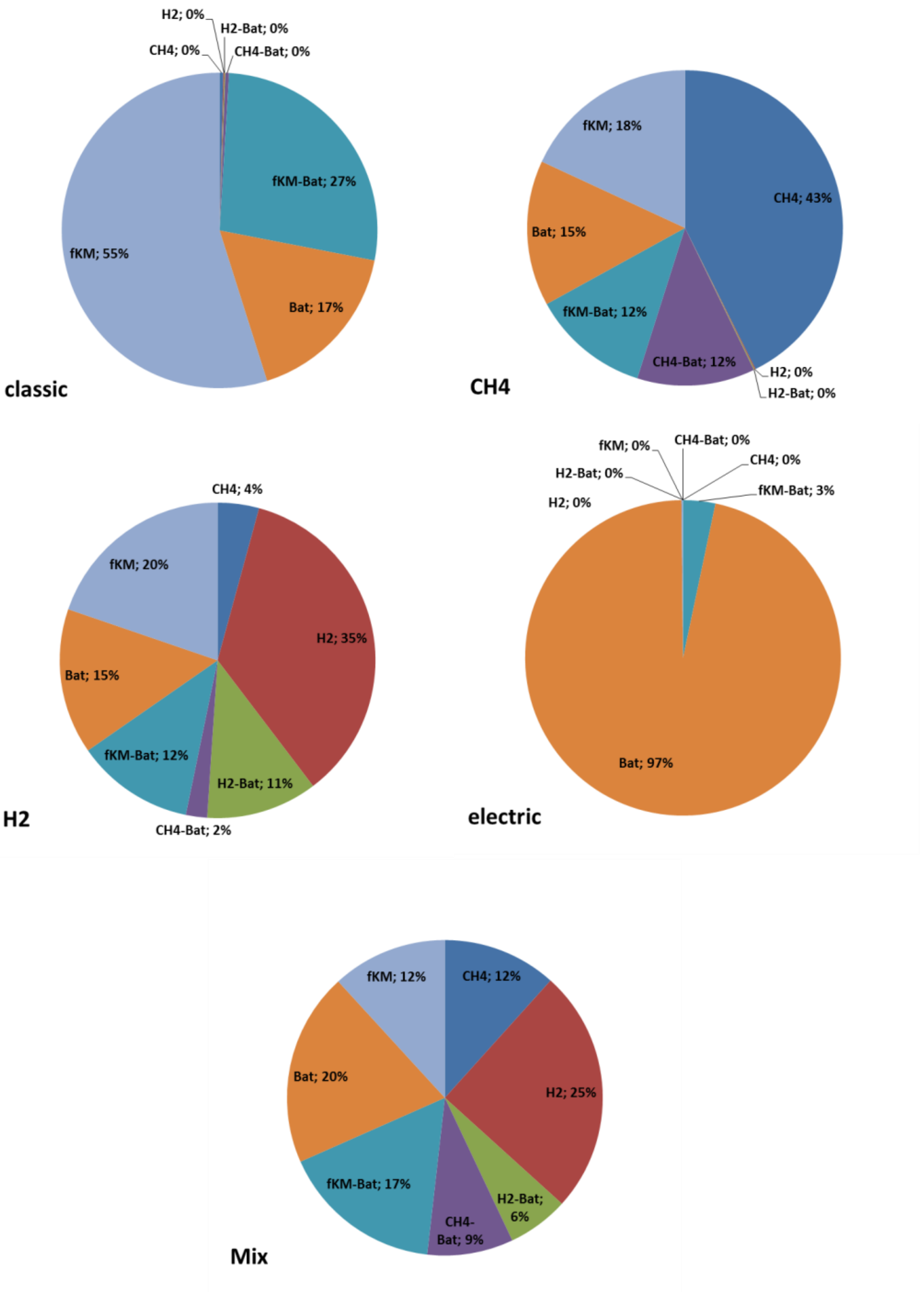


Fig. 13 Composition of the passenger car fleet in 2050 for the five investigated mobility scenarios

The following definitions apply:

Bat: vehicles with battery/electric motor

fKM: vehicles with combustion engine with liquid fuel mix

H2: vehicles with hydrogen fuel cell and electric motor

CH4: vehicles with combustion engine and gaseous fuel

fKM-Bat, H2-Bat, CH4-Bat: hybrid concepts with battery/electric motor

Except in the »electric« scenario, it is assumed in all scenarios that there is a significant increase in vehicles using batteries in connection with electric motors in the area of motorised individual mobility. However, the portion of battery-based electric vehicles without additional drive source was limited to maximum 20 % of all passenger cars in 2050. At the same time, it is assumed in these scenarios that a portion of motor vehicles uses hybrid drive concept consisting of an electric motor with battery and a combustion engine and/or fuel cell. In the modelling, it is assumed that the batteries of these vehicles can be charged via grid power (plug-in hybrids).

Fig. 13 shows the composition of the passenger car fleet in 2050 with respect to the used drive concepts for the five investigated scenarios. The respective market shares and the resulting development of the vehicle stock along the time axis in the time period from 2014 to 2050 for the five investigated scenarios can be found in Appendix 4: Vehicle development mobility scenarios.

2.3.4 Exit from Coal Power Plants by 2040

As already presented in section 2.2.3, the operation of thermal large power plants for electricity generation is not included in the optimisation. The development follows the so-called line of death, which indicates, how much power plant capacity is removed from the grid in which year [24]. To investigate the effect of an accelerated exit from coal-fired electricity generation on the development of the overall system, we have assumed in some scenario calculations that coal-fired electricity generation ends in 2040 and that the portion of coal-fired power plants is reduced faster than indicated by the line of death. This should be understood as direct response to the statements made by the German Environment Minister Barbara Hendricks in July 2015 [31], which were investigated in respective model scenarios.

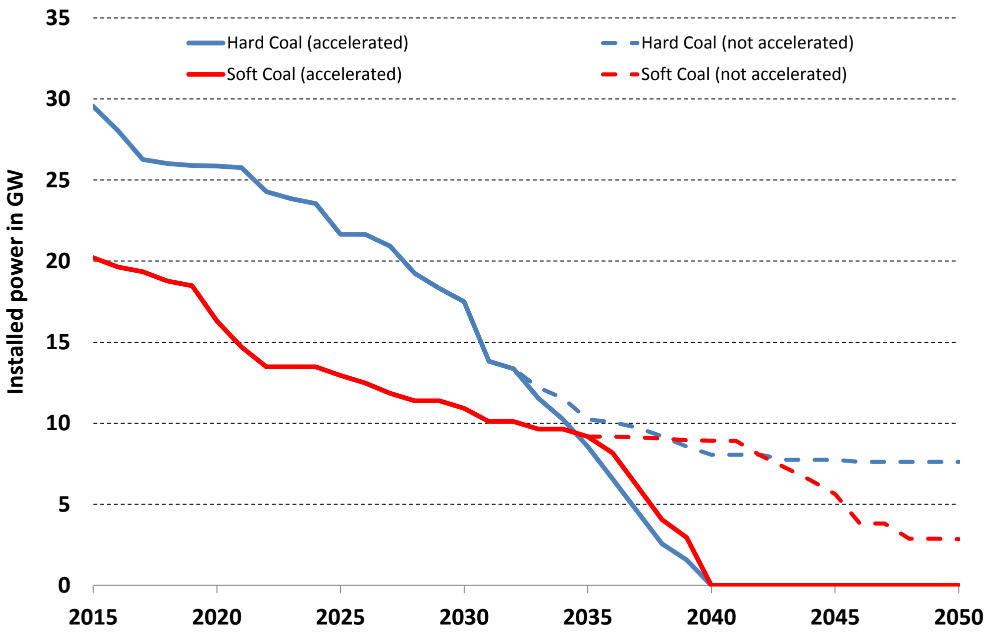


Fig. 14 Chronological development of the installed power of coal-fired power plants in the investigated scenarios. Data source: [8]

The installed power of coal-fired power plants by lignite and hard coal power plants is shown in Fig. 14. According to this, the accelerated reduction of hard coal power plants starts in 2032, and of lignite power plants in 2035. Both types of power plants stop their contribution to the power supply in the respective scenario calculations in 2040.

2.3.5 Summary of the Investigated Climate Protection Scenarios

The results of nine scenario calculations are presented in the following chapter. The respective scenarios and their assumptions relative to the target value of energy-related CO_2 emissions, energy renovations, the vehicle sector composition used, and the exit from coal-fired electricity generation are summarised in table 1. Every calculation contains a complete optimisation calculation for the given development of energy-related CO_2 emissions, respectively, to identify the transformation pathway leading to a transformation cost minimum under the given assumptions and definitions (according to section 2.2).

Tab. 1 Overview of the investigated climate protection scenarios

<table>
<tr><th>seq.no.</th><th>Target value CO_2</th><th>Energy renovation buildings</th><th>Vehicles</th><th>Coal plants</th><th>Abbreviation</th></tr>
<tr><td># 1</td><td rowspan="7">- 80 %</td><td rowspan="5">low</td><td>classic</td><td>not accelerated</td><td>80/low/class./n.a.</td></tr>
<tr><td># 2</td><td>CH4</td><td>not accelerated</td><td>80/low/CH4/n.a.</td></tr>
<tr><td># 3</td><td>H2</td><td>not accelerated</td><td>80/low/H2/n.a.</td></tr>
<tr><td># 4</td><td>electric</td><td>not accelerated</td><td>80/low/eletric/n.a.</td></tr>
<tr><td># 5</td><td>Mix</td><td>not accelerated</td><td>80/low/mix/n.a.</td></tr>
<tr><td># 6</td><td rowspan="2">ambitious</td><td rowspan="2">Mix</td><td>not accelerated</td><td>80/amb/mix/n.a.</td></tr>
<tr><td># 7</td><td>accelerated</td><td>80/amb/mix/acc.</td></tr>
<tr><td># 8</td><td>- 85 %</td><td>ambitious</td><td>Mix</td><td>accelerated</td><td>85/amb/mix/acc.</td></tr>
<tr><td># 9</td><td>- 90 %</td><td>ambitious</td><td>Mix</td><td>accelerated</td><td>90/amb/mix/acc.</td></tr>
</table>

In this context, calculations were not performed for all possible combinations of scenario variants. First, we performed optimisation calculations for the five different mobility scenarios under the same assumptions for all other boundary conditions described above. The target value of energy-related CO_2 emission was here minus 80 % relative to the reference value in 1990. Low energy renovations were assumed as well as the operation of coal-fired power plants until 2050. The “Mix” mobility scenario was then always defined for all other optimisation calculations. This should compensate for the uncertainty regarding the development of the vehicle sector. Furthermore, an ambitious energy renovation of the building sector and an accelerated exit from coal-fired electricity generation were assumed for calculations with the CO_2 reduction targets of 85 % and 90 %, as otherwise these stricter climate protection targets could not be achieved purely mathematically due to the permitted CO_2 quantities.

3 Results

This chapter presents selected results of calculations to the nine scenarios described above.

3.1 System Composition for the Investigated Scenarios

First, the system development in the area of the technologies for the investigated scenarios is shown. The different boundary conditions cause differences in the development of the system composition. This particularly applies to the expansion of converters of renewable energies, such as solar converters (photovoltaics, solar thermal energy) and onshore and offshore wind energy converters, the development of the composition of supply technologies for heat provision in buildings, the use of the biomass available to the overall system, the development of the installation of different energy storage devices, and the installation of power-to-hydrogen, power-to-gas, and power-to-fuel technologies.

3.1.1 Electricity Generation

The composition of the most important converters of renewable energies for the electricity generation, i.e., onshore wind energy converters, wind energy converters in the North and Baltic Sea (offshore), and photovoltaics for electricity generation for the nine investigated scenarios, is shown in Fig. 15. The installed power in 2050, i.e., the target year investigated, is shown.

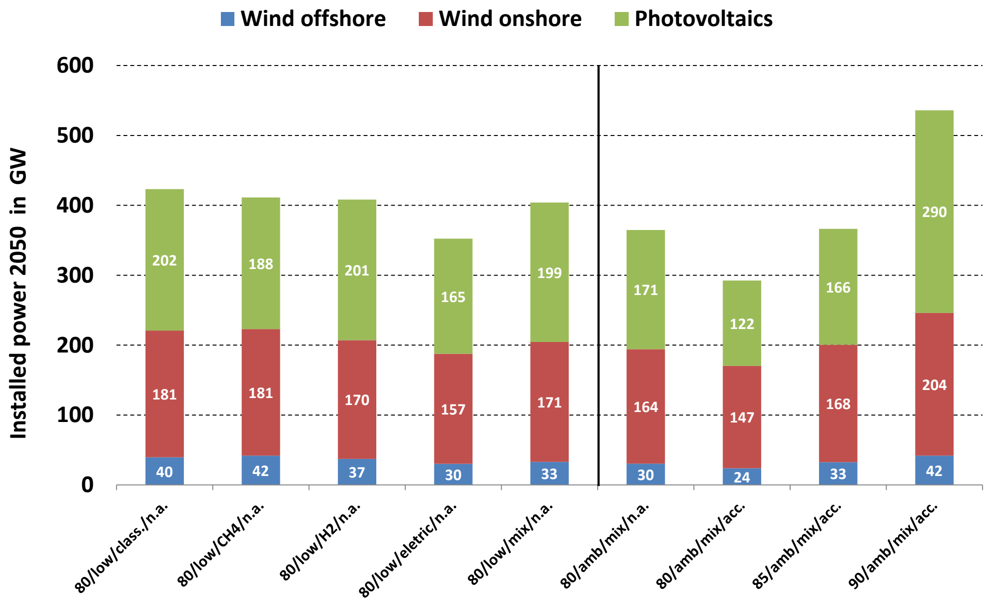


Fig. 15 Installed power of the most important converters of renewable energies (solar, wind) in 2050 for the investigated scenarios

When looking into the first five scenarios with different mobility concepts, while all other boundary conditions remain the same, it can be observed that the installed power of wind turbines and photovoltaic systems is significantly smaller in the scenario with a high portion of electric vehicles (scenario 80/low/electric/n.a.) than in the other four scenarios. The total installed power for wind turbines and photovoltaic systems is here slightly above 350 GW, while the values for the other four scenarios are slightly above 400 GW. This is explained by the higher efficiency during conversion of final energy (electricity) into useful energy (traction) of battery-electric motor drives compared to all other drive concepts.

The effect of an ambitious building energy renovation can be seen in the comparison between otherwise similar scenarios with a CO_2 reduction of 80 %, drive concept mix for mobility, and without accelerated exit from coal-fired electricity generation (80/low/mix/n.a. and 80/amb/mix/n.a.). Respectively, for the scenario with ambitious building energy renovation, the result is a significantly lower installed power of wind and solar converters. Here, the installed power is at approx. 365 GW in 2050, while the value for the scenario with lower building energy renovation is above 400 GW. An even more significant reduction is possible, if the exit from coal-fired electricity generation is realised by 2040. In the case of an ambitious building energy renovation and a drive concept mix for motor vehicles, the installed power of the power converters from solar and wind energy is at around 292 GW installed power in 2050 (80/amb/mix/acc. scenario).

All scenarios discussed so far lead to a reduction in energy-related CO_2 emissions by 80 %. A significant increase in the installed power is required, if the CO_2 emissions should be reduced further, i.e., by 85 %. In this case, the total installed power for solar and wind-based electricity generation amounts to 412 GW – or by 90 % with a total installed power of 536 GW[1].

Ensuring the supply with electricity at any point in time requires the installation of generators that will be available if renewable energies cannot provide sufficient power. The composition of the installed power for the complementary power generators from different fossil and renewable energy carriers considered in the model is shown in Fig. 16.

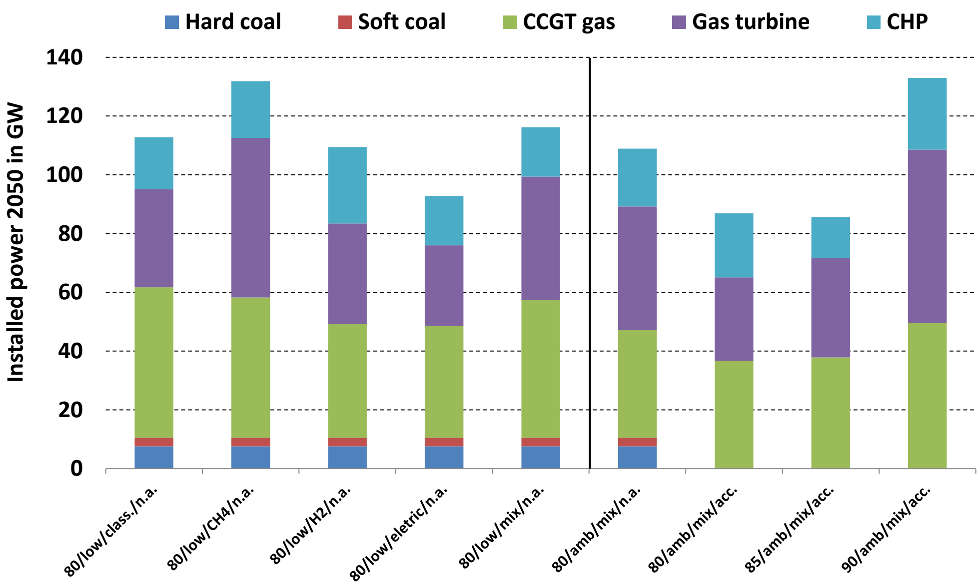


Fig. 16 Installed power of complementary power generators in 2050 for the investigated scenarios. For the scenarios with not accelerated exit from coal-fired electricity generation, the power of coal power plants still installed in 2050 is presented as well.

Overall, a high portion of CCGT power plants (between 36 GW and 55 GW) operated with natural gas and/or a mix of fossil and renewable natural gas can be seen in all

[1] The energy balance can only be met in this scenario, if higher installed powers are permitted for wind turbine and photovoltaic systems. Thus, the set limits deviate in this case from the limits in other calculations.

scenarios. CHP power plants, either as systems in heating networks or as systems in individual buildings, have an installed power between 15 GW and 26 GW. Various quantities of gas turbines are required. As optimisation result, gas turbines are installed as cost-effective, however less efficient power generators compared to CCGT power plants mainly for peak powers only required infrequently.

Similarly to converters from solar and wind energy into electricity, an ambitious energy renovation and accelerated exit from coal-fired electricity generation lead in the case of complementary power generators to a lower required installed power as in the respective comparison scenarios with moderate energy renovation and/or coal-fired electricity generation until 2050. The total power for complementary power generators amounts from barely 90 GW to approx. 130 GW. The maximum values are required for the scenario with natural gas vehicles dominating the vehicle market (80/low/CH4/n.a.) and for the 90-% scenario (90/amb/mix/acc.). Among others, the high required installed power of power plants in the 90-% scenario is caused by that fact that heat is provided almost exclusively through electric heat pumps (see next section).

3.1.2 Heat Supply and Building

The number of building renovation cases was defined in all nine investigated scenarios (see section 0). However, the number of buildings renovated to the current new construction standard (referred to as »fully renovated«) or beyond (referred to as »highly efficient«) is left open and is determined via optimisation. The result is shown in Fig. 17.

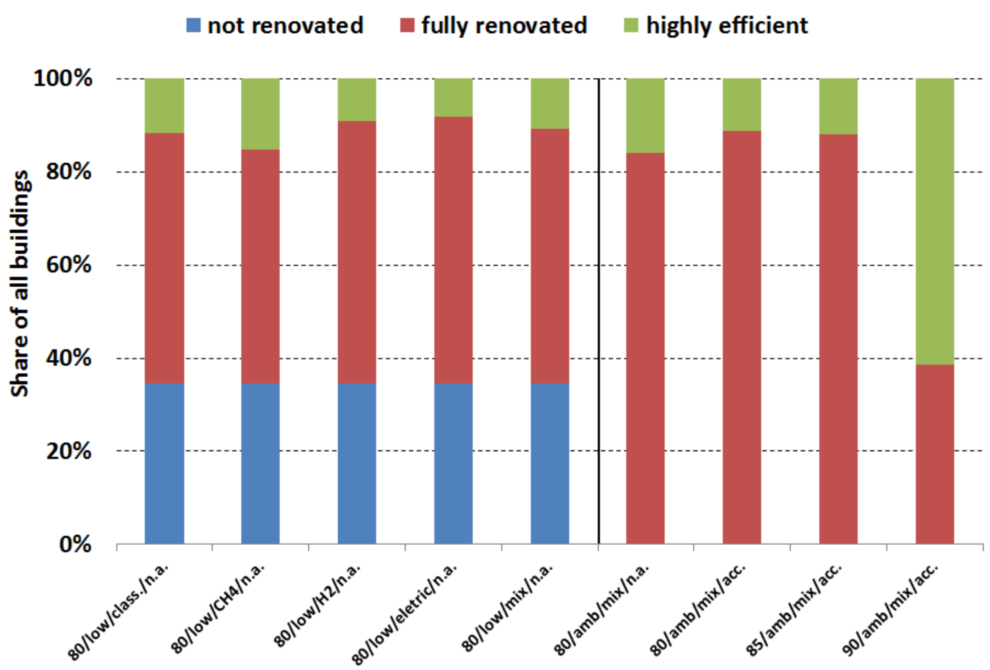


Fig. 17 Renovation status of the building stock in 2050 for the investigated scenarios.

While in the case of a low renovation rate, still 35 % of all buildings remain not renovated in 2050, an ambitious renovation rate results in all buildings being renovated in 2050, either in compliance with the »fully renovated« or the »highly efficient« standard. However, the »highly efficient« standard is only achieved by approx. 10 % to 15 % of the buildings in all scenarios, except the 90-% scenario (90/amb/mix/acc.). In the case of the 90-%-scenario, the portion of buildings with »highly efficient« standard dominates and is greater than 60 % of all buildings. In this scenario, the available amount of fossil energy carriers is so small that the comparatively expensive, large-scale energy renovation is advantageous.

The composition of heat supply technologies for the building stock in 2050 is presented for the investigated scenarios in Fig. 18. Heat pumps (electric and with fuel) are the dominant heating technology in all scenarios. Their share is between approx. two thirds up to approx. 90 %. The share of heating systems with district heat connection is between approx. 15 % and approx. 20 %, respectively. The share of combustion-based technologies (gas boiler, gas heat pump, small CHP) fluctuates severely. In the 90-% scenario, combustion-based technologies are of no importance anymore. Due to the small amount of available fossil energy carriers, the amount of fuel is so small that demand is fully covered by district heat and electric heat pumps. At the same time, the ground-coupled and, thus, more efficient heat pump technology dominates clearly. In contrast, in the comparable scenario with 80 % CO_2 reduction (80/amb/mix/acc.), a sufficient amount of fuel is still available so that combustion-based technologies cover more than 50 % of all heating systems. Biomass is of no importance for the heat supply in the building sector. In the overall concept, it is obviously more cost-efficient to use the limited biomass resources for other applications.

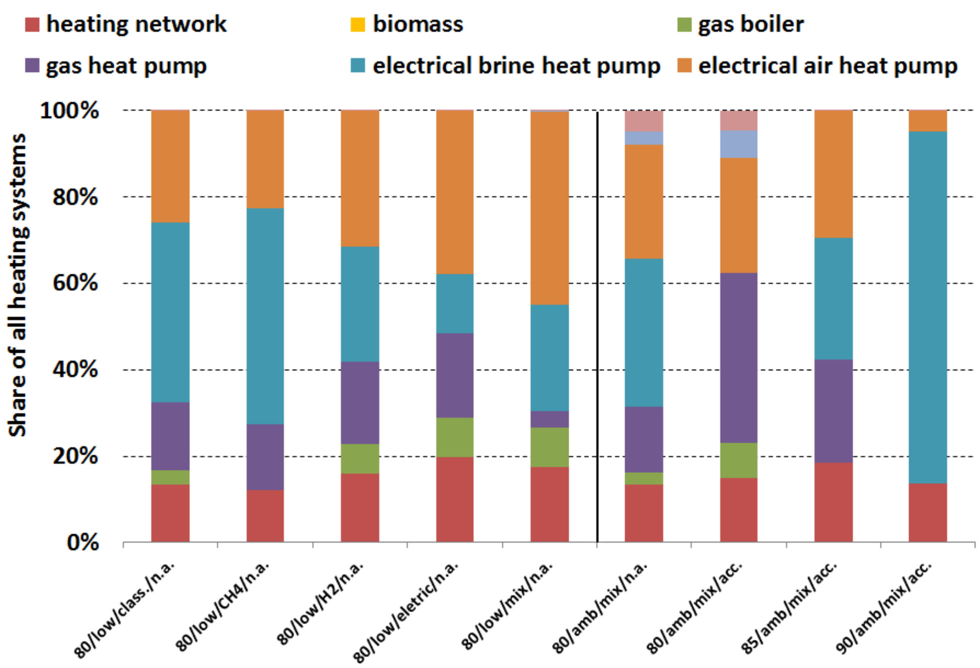


Fig. 18 Composition of the heat supply technologies for the building stock in 2050 for the investigated scenarios.
The following definitions apply:
el. HP – brine: electric heat pump with ground heat source
el. HP – air heat: electric heat pump with air heat source
Hybrid HP electric heat pump combined with gas boiler

Solar thermal energy is a possible direct use of renewable energies in the heating area. Three applications were investigated here: use in the individual building combined with other heat supply technologies, use in connection with heating networks, and the application for low-temperature processes in trade and industry. Fig. 19 shows the installed power of solar collectors for the nine investigated scenarios.

In almost all scenarios, decentralised systems in individual buildings represent the largest share. The installed power is in the order of magnitude of 60 GW in all investigated cases. Application in low-temperature industrial processes assumes second place. Here, the installed power is between 42 GW and 54 GW. The installed power of solar thermal energy systems coupled with heat networks is between 25 GW and 45 GW. The total installed power of solar thermal energy systems is between 133 GW (80/low/H2/n.a. scenario) and 159 GW. This largest installed power corresponds to the scenario with classic drive concept mix in the mobility sector and low renovation. Based on the installed power of solar thermal energy systems, the corresponding collector area (aperture area) can be calculated. It is the simple result of a conversion factor of 0.7 kW_{th} per m² aperture area. Thus, a power of 133 GW corresponds to an area of 190 million m² and a power of 159 GW to an area of 227 million m².

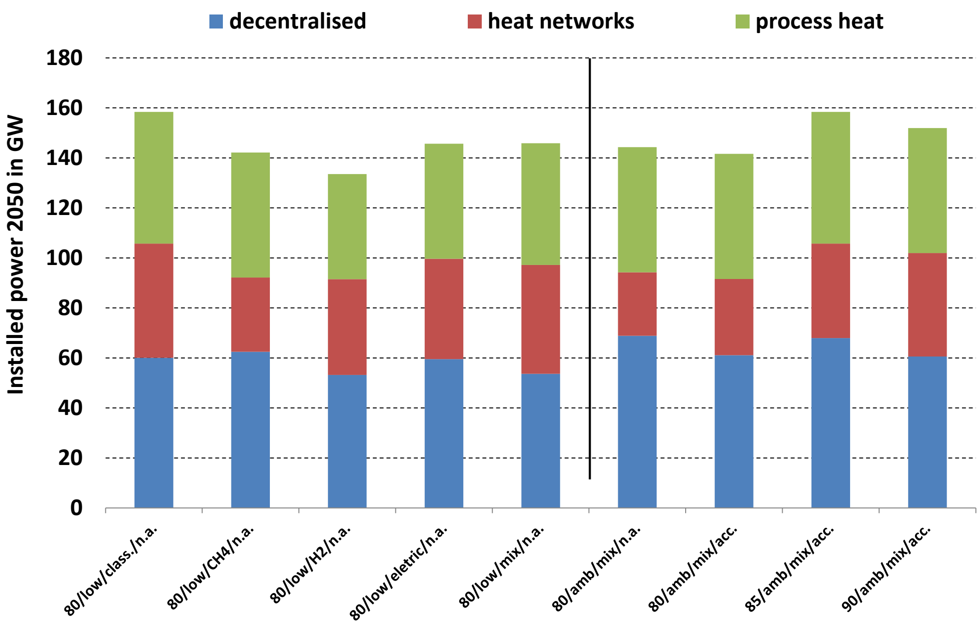


Fig. 19 Installed power of solar thermal energy systems in 2050 for the investigated scenarios.

3.1.3 Biomass Usage

The installed power values of converter systems are shown in Fig. 20.

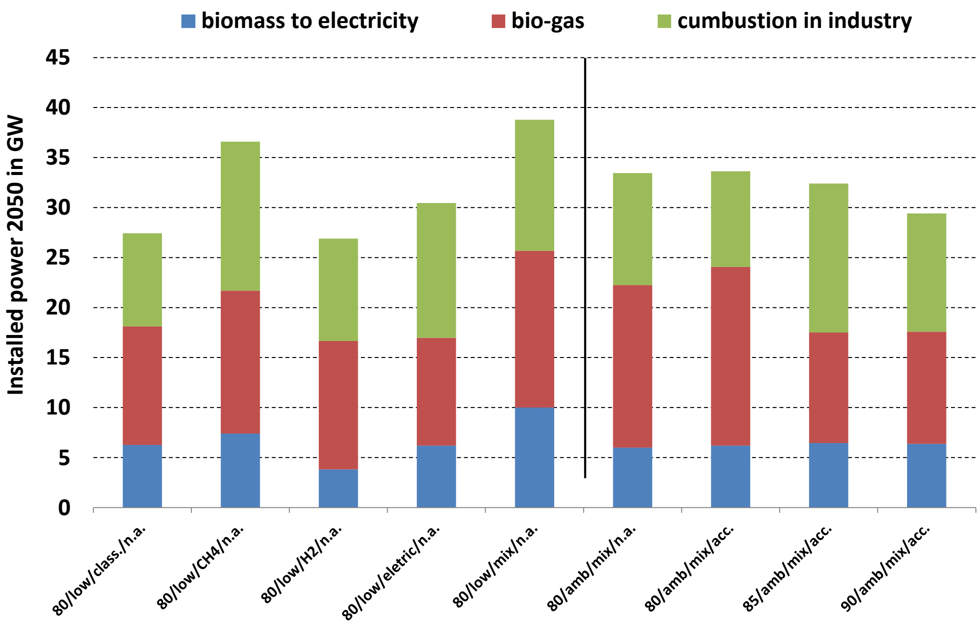


Fig. 20 Installed power of systems for further conversion of biomass in 2050 for the investigated scenarios.

The results show that only three conversion options are used of the many biomass usage possibilities (according to the information in section 2.2) regardless of the investigated scenario: biomass electricity generation in individual systems, the conversion into natural biogas, which is mixed with fossil natural gas and possibly methane from renewable energies and distributed via the gas network, and biomass combustion for high-temperature industrial applications.

The total installed power for all systems of these types is between approx. 27 GW and approx. 40 GW.

3.1.4 Energy Storage Systems

Within the scope of modelling, pumped-storage power plants and stationary batteries are investigated as short-term energy storage systems for storing electricity, and sensible heat storage with water as storage medium in individual buildings and heat networks for heat storage. Short-term storage devices are storage devices typically used for temporarily storing energy for a few hours – e.g., from day into the night or from weekend to mid of the week. The installed capacity of pumped-storage power plants was not achieved via optimisation. An increase to 70 GWh was assumed in all scenarios (see section 2.2.3). The calculation results are shown in Fig. 21 for electricity storage devices and in Fig. 22 for heat storage devices. The installed capacity is presented in GWh.

The installed capacity for batteries is between approx. 40 GWh and slightly over 120 GWh in the 90-% scenario (90/amb/mix/acc. scenario). The lowest value occurs in the scenario with a high share of vehicles with battery and electric motor (80/low/electric/n.a.). This is caused by the high capacity of batteries in electric vehicles, which are available to the system as short-term storage in this scenario.

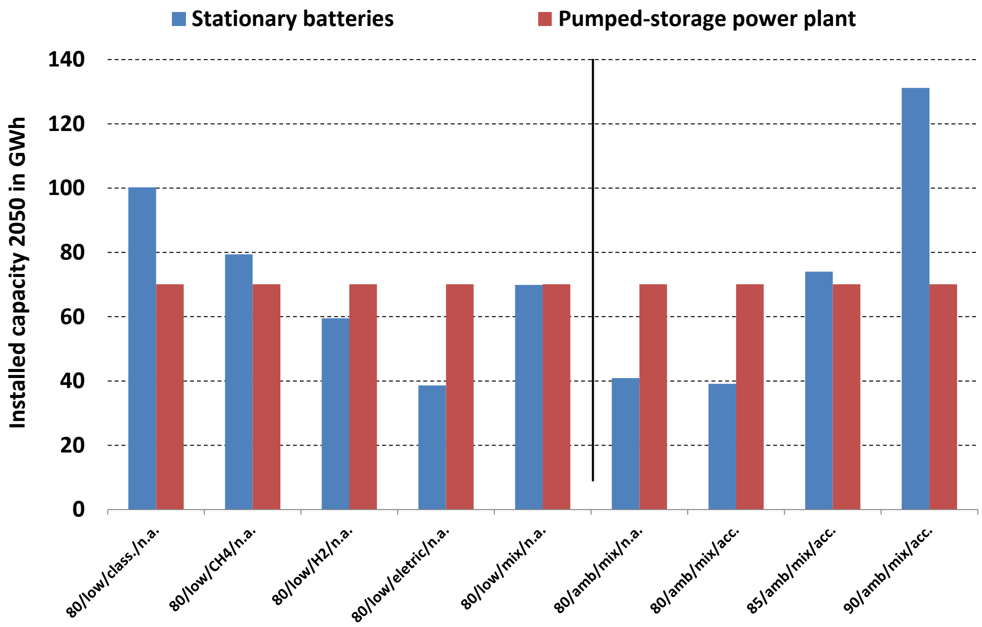


Fig. 21 Installed capacity of short-term storage for electricity in 2050 for the investigated scenarios.

The total capacity for decentralised heat storage installed in individual buildings is between approx. 450 GWh and approx. 600 GWh. On the one hand, the function of these storage devices is heat storage in connection with solar thermal energy systems to balance between heat supply and heat demand in the buildings. On the other hand, their function is heat storage in connection with electric heat pumps for flexible heat pump operation beneficial to the network.

For heat storage coupled to heat networks, the total installed capacity is between almost 400 GWh and approx. 750 GWh. These storage devices are responsible for absorbing heat from large heat network-bound CHP plants and heat from solar thermal energy systems. Furthermore, they enable – similar to decentralised heat storage – the absorption of excess electricity in the case of high negative residual loads (see the remarks regarding operations management in section 0). An analysis of the medium charging and discharging times shows that large centralised heat storage devices are on average charged and discharged 2 to 3 times a week. Thus, they do not function as long-term or seasonal storage.

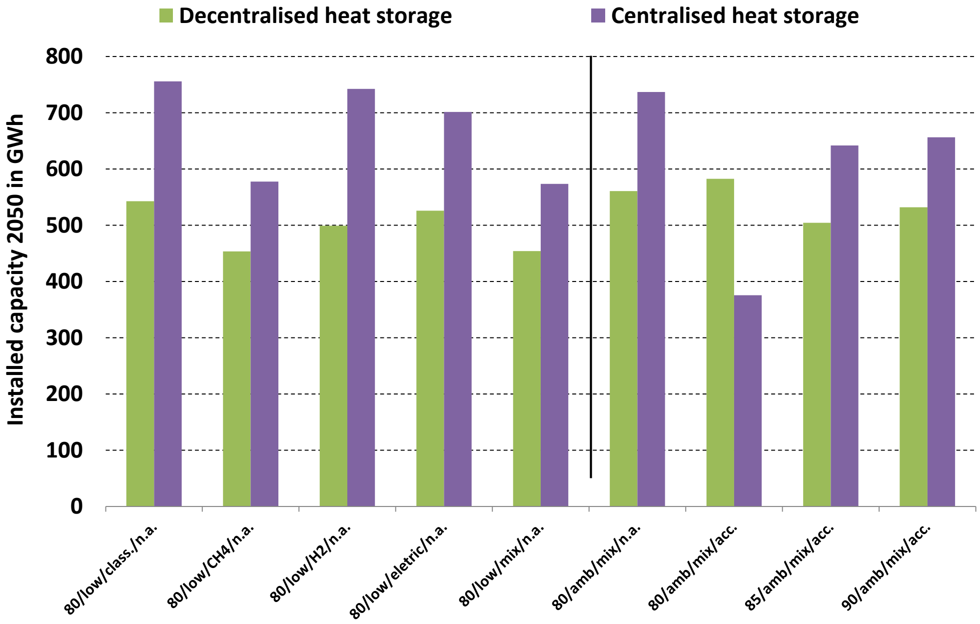


Fig. 22 Installed capacity of short-term storage for heat in 2050 for the investigated scenarios.

3.1.5 Power-to-Hydrogen/-Gas/-Fuel Technologies

In the case of limited fossil resources for the provision of storable energy, different conversion technologies can be considered to produce storable, synthetic energy carriers from electricity generated using renewable energies. These energy carriers function in the system as long-term energy storage. They are generally generated from renewable energy and can be used in the systems in various forms depending on the type of the generated energy carrier.

On the one hand, we investigated the production of hydrogen (referred to as »electrolysis«) and its direct use as addition to the natural gas network as well as the use as fuel in motor vehicles that use hydrogen in connection with fuel cell and electric motor. On the other hand, we investigated the conversion into synthetic methane in combined systems of electrolysis and downstream Sabatier process (referred to as »Sabatier«) (here, the installed power refers to the electric power of the overall system including electrolysis). Finally, the conversion of hydrogen into liquid fuels was considered as further option. The last two mentioned technologies use outside air as CO_2 source.

The result according to Fig. 23 shows that a significant capacity of such converters is required in all investigated scenarios to ensure security of supply in the context of the overall system. The total install power for these converters is between approx. 80 GW and approx. 130 GW for all scenarios except the 90-% scenario. The 90-% scenario requires a significantly higher capacity of 180 GW. This is due to the small amount of fossil energy carriers (mainly fossil natural gas) still available for all energy applications. Residual electricity generation and in particular the mobility sector require energy carriers with high energy density. The available biomass is not sufficient.

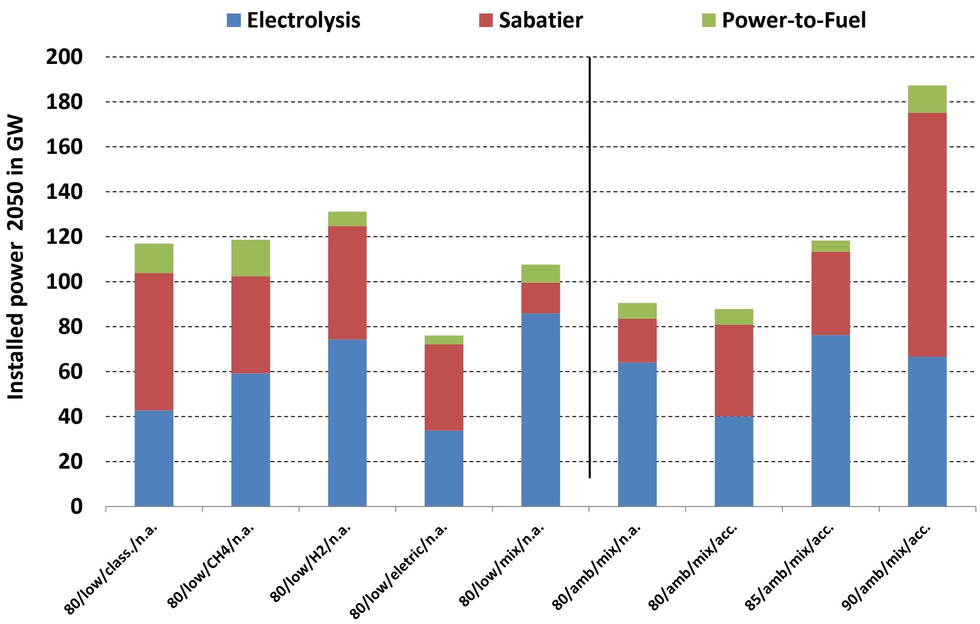


Fig. 23 Installed power of converters for the production of fuels from renewable energy in 2050 for the investigated scenarios.

3.1.6 System Composition Summary

Summarising, the analysis of the investigated nine scenarios shows that the degree of electrification of road mobility, the degree of renovation of the building stock, and – even more decisive – the time of the exit from coal-fired electricity generation have a central influence on the technical composition of an energy system in line with climate protection in 2050. With respective implementation, all three factors lead to a significantly lower required installed power of solar and wind energy systems than in the case of respective comparison scenarios. Besides the costs that are analysed in the following section, social acceptance is particular important for the expansion of wind-based electricity generation plants (and solar-based plants at least in the case of open space plants) in the implementation of the energy transformation. In this respect, scenarios should be preferred that require an as small as possible installed power of these plants.

The target value for the reduction of energy-related CO_2 emissions has significant influence on the system composition and the required installed power of all generators and converters. A reduction of energy-based CO_2 emissions by 90 % relative to the initial value in 1990 requires a total installed power of photovoltaic plants and wind turbines of approx. 536 GW even in the case of ambitious energy renovation and accelerated exit from coal-fired electricity generation. At the same time, approx. two third of all buildings would have to be renovated in line with a very high energy standard. The largest share of the installed power of the compared scenarios is also required for most of the other technologies, such as complementary electricity generation, plants for biomass conversion, and plants for the production of synthetic fuels from renewable energies. At the same time, combustion processes would be completely displaced from the heat supply and ground-coupled electric heat pumps become the dominating heating technology.

3.2 Costs for the Investigated Scenarios

The cost discussion is of decisive importance in the social debate regarding the energy system transformation. For this reason, a solid as possible cost analysis investigating the entire transformation process is important. A detailed cost analysis is carried out in this section. The different cost types (investments, financing costs, operating and maintenance costs, fuel costs) are investigated and compared under different assumptions and boundary conditions, such as different growth rates for import prices of energy resources or different scenarios of cost assignment to CO_2 emissions.

3.2.1 Cumulative Costs without Price Increase and CO_2 Emission Costs

On the one hand, the transformation of the energy system means that new, additional plants are installed in the area of energy conversion and storage – e.g., photovoltaic plants and wind turbines or stationary batteries and hydrogen production plants. On the other hand, it means that existing plants, e.g., in the area of heat supply for buildings, are replaced by new and partly different devices – e.g., the replacement of gas boilers with heat pumps. This requires respective investments, including replacement investments for old systems that are decommissioned after service life expiration. These investments are compared to the costs for import and local generation of fossil energy carriers, which decrease due to the stepwise reduction in use of fossil fuels.

Fig. 24 shows the cumulative costs for the nine investigated climate protection scenarios in comparison. They consist of investments, fuel costs (fossil energy carriers, biomass), operating and maintenance costs, as well as finance costs. In addition to the values for the nine climate protection scenarios, the respective values of the reference system are provided as well. Here it is assumed that the energy system remains stable as in 2014 and is further operated without retrofits. Fig. 24 also applies to flat import costs for fossil energy carriers. No CO_2 emission costs (hence, e.g., CO_2 certificates or CO_2 emission taxes) were considered either.

The cumulative total costs are between approx. €5,300 billion and €5,800 billion for all climate protection scenarios except the 90-% scenario (90/amb/mix/acc.), while the value for the 90-% scenario is approx. €6,600 million. Of the five scenarios that compare different developments in the area of drive concepts for road mobility, while keeping all other boundary conditions the same, the scenario with a dominant development of drive concepts with battery/electric motor (80/low/electric/n.a.) are the most cost-effective with cumulative total costs of €5,380 billion. This corresponds to the results presented in the previous section, according to which this scenario leads to the smallest installed power of wind turbines and photovoltaic plants and the smallest investment values in the area of many other system components. The 80-% scenario with ambitious energy renovation of buildings, a mix of vehicle concepts, and an accelerated exit from coal-fired electricity generation (80/amb/mix/acc.) achieves similar values. The respective scenario with a reduction of energy-related CO_2 emissions by 85 % (85/amb/mix/acc.) leads to slightly higher values. For the first scenario, the value of cumulative total costs amount to €5,260 billion, and for the second scenario to €5,340 billion.

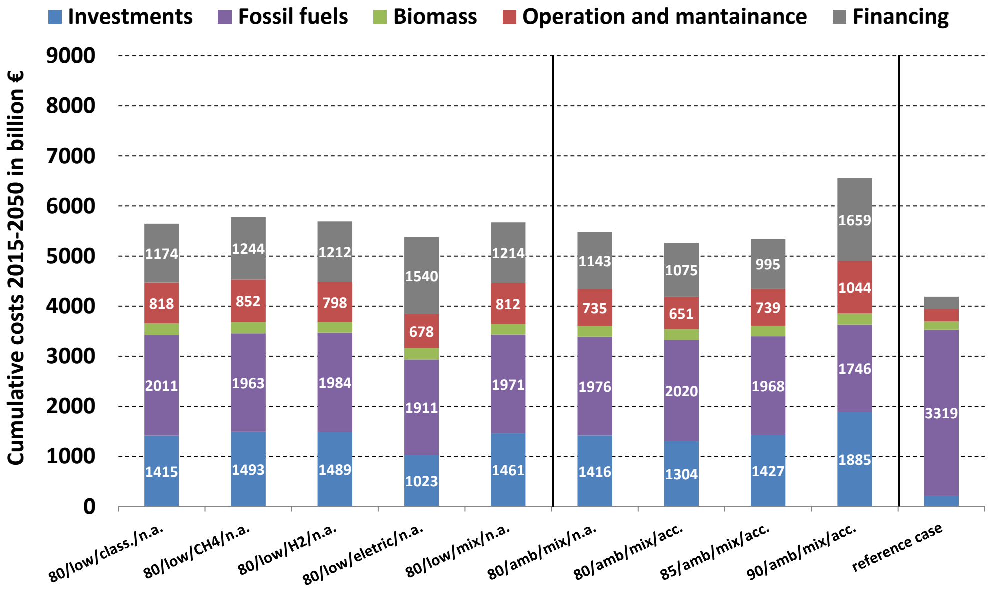


Fig. 24 Cumulative costs from 2015 to 2050 for the investigated climate protection scenarios and cumulative costs for a reference case (see text). The presentation applies for the following conditions:
- No increase in import costs for fossil energies
- No CO_2 emission costs

The value of the cumulative total costs in the reference case amounts to approx. €4,200 billion. It is thus approx. €1,070 billion lower than the lowest value of the investigated climate protection scenarios. If these additional costs of €1,070 billion are equally distributed to 2014-2050, the result is yearly additional costs of approx. €30 billion, which corresponds to approx. 0.8 % of the German gross domestic product in 2013. The costs for fossil fuels dominate in the reference case. With approx. €3,300 billion, they correspond to close to 80 % of the cumulative total costs. As this reference system represents an unchanged continuation of the current system composition, investments are merely required for the replacement of expiring power plants and plants to be replaced for the use of renewable energies. They are thus significantly smaller than in all climate protection scenarios. The operating and maintenance costs as well as the financing costs are lower as well, respectively.

An important question is why the costs for fossil energy carriers in the investigated climate protection scenarios do not drop similarly sharply as the CO_2 emission. This is justified by the fact that the cost-effective energy carriers lignite and hard coal are mainly displaced from the system that show high specific CO_2 emissions at the same time. In comparison, more expensive – but, with respect to energy content, CO_2 poorer – energy carriers, such as natural gas, crude oil, and oil products, that must mainly be imported, are used in all climate protection scenarios up until 2050.

3.2.2 Consideration of Price Increases for Fossil Energy Carriers

From today's point of view, the long-term development of the import costs for fossil energy carriers is difficult to predict. In particular, if climate protection policies become effective globally, this should generate price pressure towards no or minor price increases only for fossil energy resources. In the graphs in Fig. 25 to Fig. 27, real price increases of 2 % (Fig. 25), 3 % (Fig. 26), and 4 % (Fig. 27) were assumed for mainly imported fossil energy carriers, i.e., natural gas, crude oil, and hard coal. Constant prices were assumed for all other energy carriers, including biomass resources. The calculations still do not consider CO_2 emission costs. Besides that, the graphs are structured identically as Fig. 24 from previous section 3.2.1.

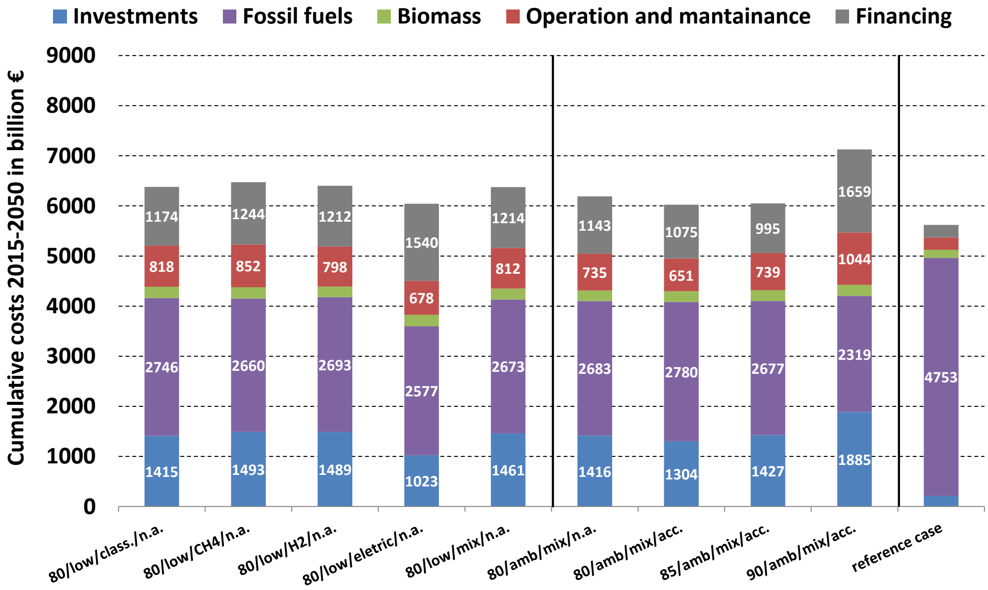


Fig. 25 Cumulative total costs of the investigated scenarios and the reference case. The presentation applies for the following conditions:
- 2 % yearly price increase for the import costs of fossil energies
- No CO_2 emission costs

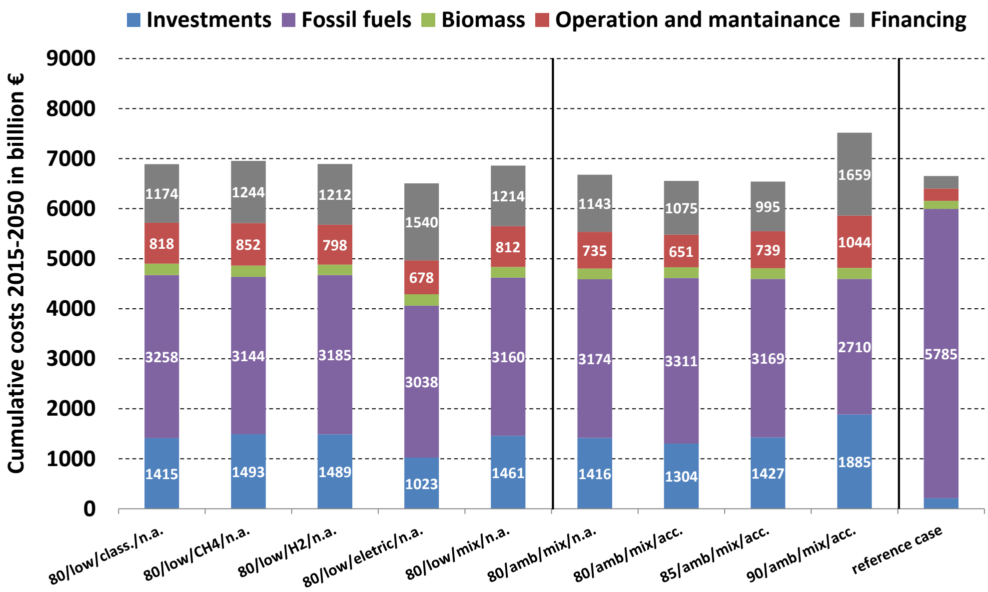


Fig. 26 As Fig. 25, however for the following conditions:
- 3 % yearly price increase for the import costs of fossil energies
- No CO_2 emission costs

Overall, it becomes obvious that with respect to costs, climate protection scenarios become the more competitive, the higher the price increases for imported fossil energy resources are – as expected. This is rather obvious. However, the investigations deliver quantitative values. In the case of an import price increase of fossil energy carriers by 3 % per year, the cumulative total costs for several investigated scenarios is approx. 2 % lower than the reference case. This includes the scenario with a very portion of electric mobility (80/low/electric/n.a.) and the scenarios with vehicle mix, ambitious energy renovation, and accelerated exit from coal-fired electricity generation that lead to a reduction of energy-related CO_2 emissions by 80 % or 85 % (80/amb/nix/acc. and 85/amb/mix/acc.). Overall, the scenarios with high CO_2 reduction become the more cost-effective, the higher the price increase for imported fossil energy carriers is. In the case of an increase in the import prices for fossil energy carriers by 4 % per year, even the 90-% scenario leads to slightly higher cumulative total costs than the reference scenario.

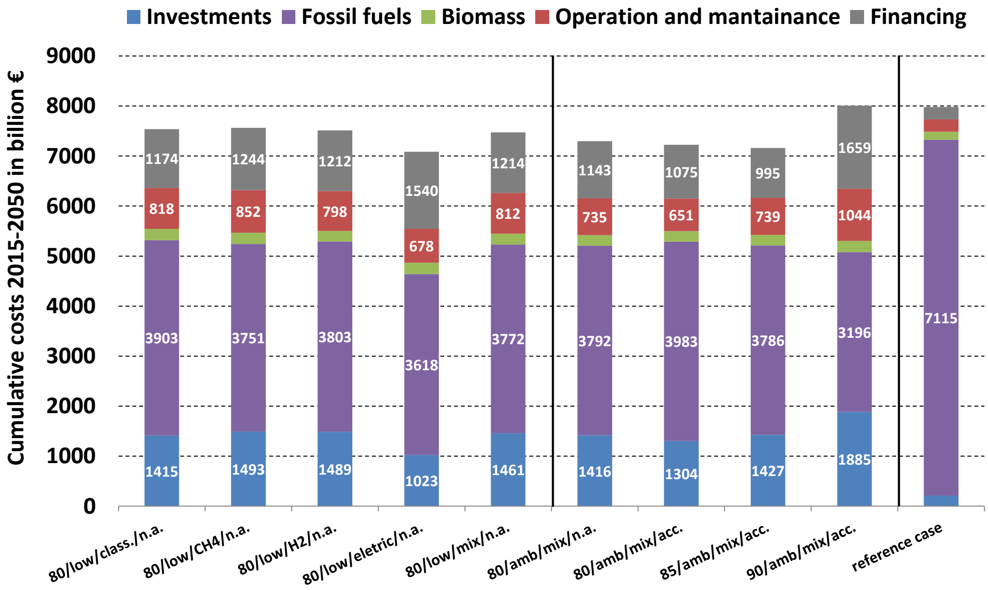


Fig. 27 As Fig. 25, however for the following conditions:
- 4 % yearly price increase for the import costs of fossil energies
- No CO_2 emission costs

3.2.3 Consideration of CO_2 Emission Costs

Costs for CO_2 emissions lead to cost increase of systems with high emission values. At this point, it is not important how such costs are charged (e.g., CO_2 tax, certificates). However, it should only be investigated, how such costs influence the cumulative total costs of the investigated systems.

Initially, we analysed, how high a constant cost value charged for CO_2 emissions over the entire period from 2014 to 2050 would have to be so that the scenario with 85 % CO_2 reduction results in the same cumulative total costs as the reference system. At the same time, it was assumed that the import prices for fossil energy resources and all other energy carriers remain constant. The result is a value of slightly over €100 per ton. Fig. 28 shows the cumulative total costs for all scenarios at this constant value.

However, a steady development of CO_2 emission costs is most likely more realistic. To map this, we used the cost function for CO_2 emissions presented in Fig. 29 in a next step. This function assumes a constant increase in costs for CO_2 emissions until 2030, followed by constant costs of €100 per ton (see Fig. 29). Here it was also assumed that the import prices for fossil energy carriers remain constant.

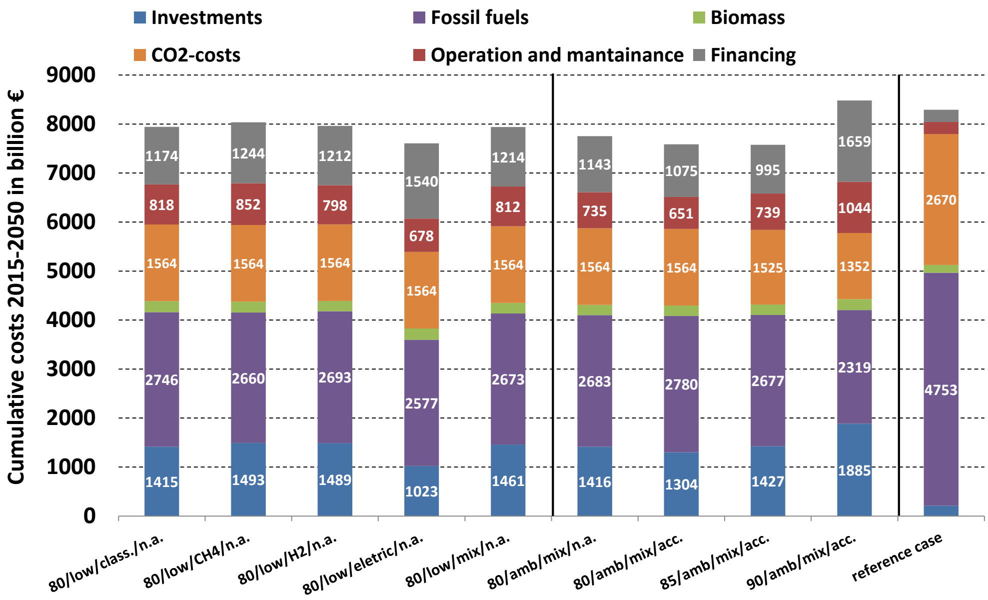


Fig. 28 Cumulative costs of the investigated scenarios and the reference case. The presentation applies for the following conditions:
- No price increase in the import costs of fossil energies
- CO_2 emission costs constant at €102/ton over the entire investigation period

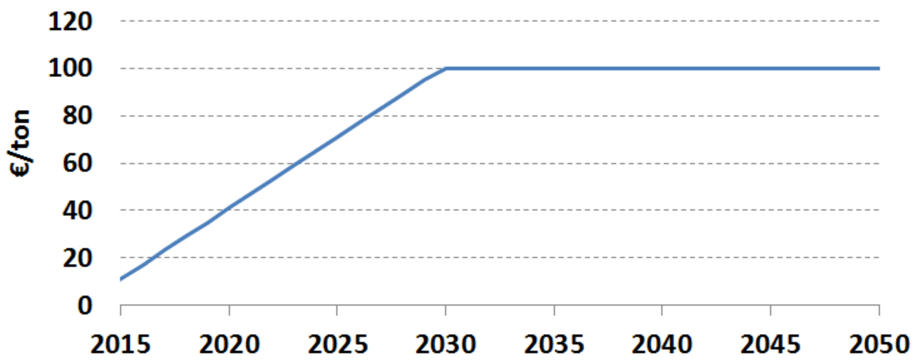


Fig. 29 Profile of the assumed costs charged for CO_2 emissions

For this case – i.e., for a development of the costs charged for CO_2 emissions according to Fig. 29 and constant import prices for fossil energy carriers– the resulting cumulative total costs for the compared scenarios can be seen in Fig. 30. In this case, the 80/amb/mix/acc. Scenario leads to almost identical cumulative total costs as the reference case.

If further price increases in the amount of 2 % per year are assumed for imported fossil energy resources – this corresponds to close to doubled values by 2050 – the resulting cumulative total costs for the compared scenarios can be seen in Fig. 31. The scenario with a reduction in energy-related CO_2 emissions (85/amb/mix/acc.) is the most cost-effective scenario under these conditions and leads to cumulative total costs that are approx. €600 billion (or 8 %) lower than in the reference case.

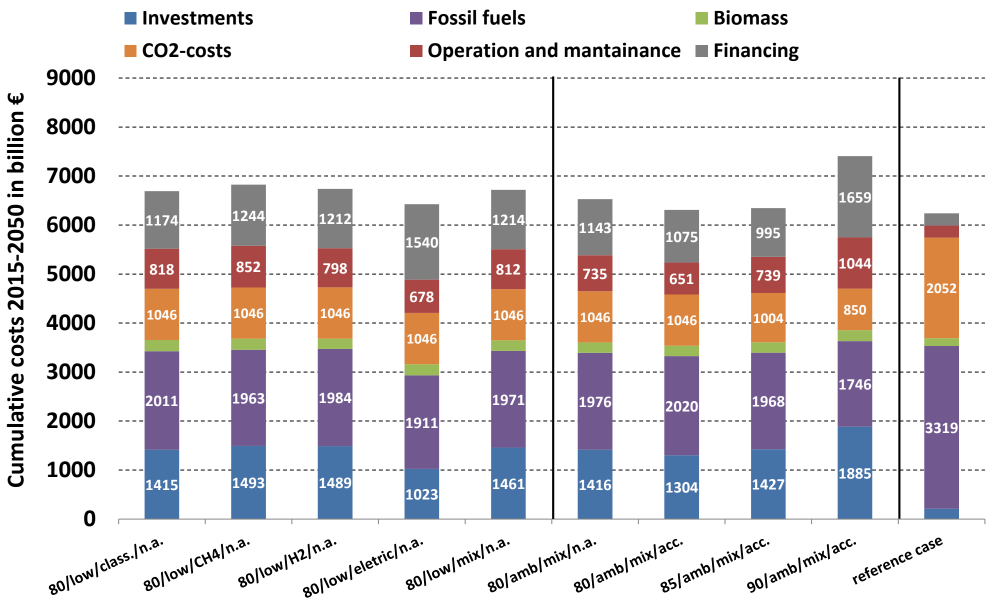


Fig. 30 Cumulative costs of the investigated scenarios and the reference case. The presentation applies for the following conditions:
- No price increase in the import costs of fossil energies
- CO_2 emission costs according to Fig. 29

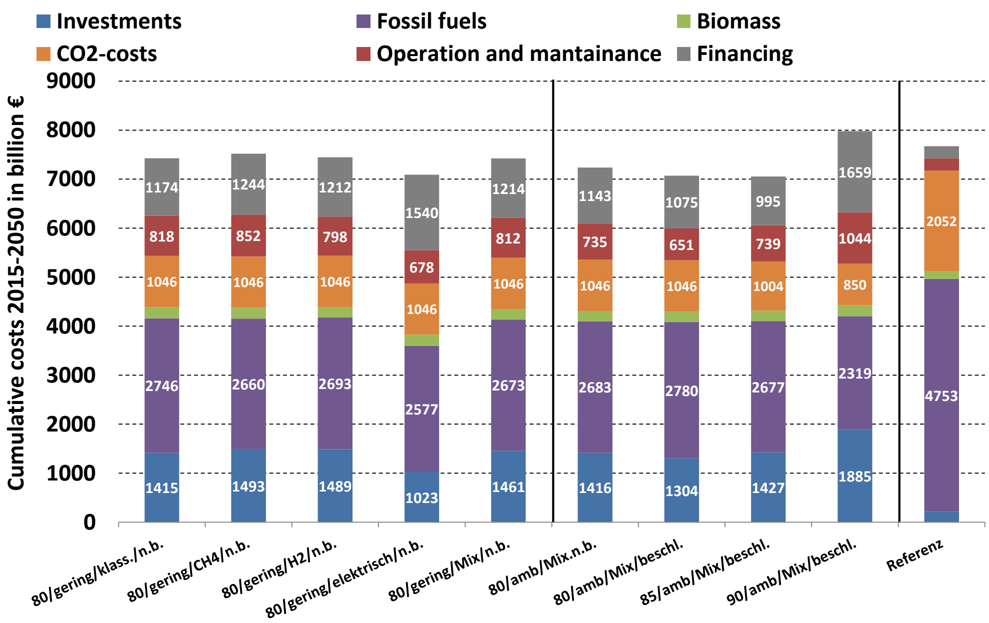


Fig. 31 Cumulative costs of the investigated scenarios and the reference case. The presentation applies for the following conditions:
- 2 % yearly price increase for the import costs of fossil energies
- CO_2 emission costs according to Fig. 29

Overall, it can be seen that with respectively increasing prices for imported fossil energy resources and/or high costs charged for CO_2 emissions, the cumulative total costs of the most cost-effective climate protection scenarios are similarly high or lower than the costs of the investigated reference system, respectively.

3.2.4 Cost Analysis Summary

Summarizing it can be said that the transformation of the energy system is not a self-propelling economic success. The required significant expansion and retrofit investments can be compensated in some of the investigated climate protection scenarios – in particular in the scenarios with ambitious energy renovation of the building sector and an accelerated exit from coal-fired electricity generation (80/amb/mix/acc. and 85/amb/mix/acc.) – over the investigated period from 2014 to 2050 through the cost savings for fossil fuels (see Fig. 24) in a macro-economic analysis. However, further costs are incurred for investment financing as well as operation and maintenance of the many hundreds of thousands of individual plants. Taking into account these costs, the retrofit and additional costs can only be arithmetically compensated through saved costs for fossil fuels, if either the prices for imported fossil energy carriers increase by approx. 3 % per year or if high CO_2 emission costs are charged (or if a respective mix of price increases and CO_2 emission costs is given), respectively.

If the costs for imported fossil energy carriers remain at the current level as well as the costs charged for CO_2 emissions – hence, approx. €5 per ton – the cumulative additional costs of the 85-% scenario would amount to approx. €1,100 billion in comparison to the reference scenario. If these additional costs are equally distributed to the years 2014-2050, the result is yearly additional costs of approx. €30 billion, which corresponds to approx. 0.8 % of the German gross domestic product in 2013.

When analysing these results, it must be pointed out that our analysis of the energy system was carried out independently from the economy. However, the quantity structures resulting from our model calculations can be used as basis for a comprehensive economic study with complete added value analyses. Here, at this point, some qualitative statements are possible only. For example, certain portions of the retrofit and expansion investments will lead to added value in Germany in the course of the energy system transformation, even if the sub-components are imported for some technologies. Plant installation will always take place on site, which will respectively contribute to added value. The same applies to plant operation and maintenance, which is also carried out on site. In contrast, only a small extent of local added value is lost due to the continuously decreasing import of fossil energy carriers, e.g., due to the lower demand for the conversion of crude oil into different oil products.

Another aspect concerns external energy supply costs. Except in the investigations regarding the effect of costs charged for CO_2 emissions, external costs were not considered in our entire analysis. A detailed quantitative analysis would be possible based on the quantity structures resulting from our analyses for the investigated climate protection scenarios. Here, at this point, a qualitative statement is possible only: considering external costs, e.g., resulting from environmental effects due to the reduction of fossil fuels (e.g., lignite coal), would very likely increase the costs of the investigated reference system – i.e., of the unchanged further operation of our energy system in the current form – significantly more than a retrofitted energy system that is mainly based on renewable energies.

4 Analysis of the 85-% Scenario

In the overall analysis, the scenario with 85 % CO_2 reduction, ambitious energy renovation of the building stock, a mix of future vehicle drives, and the exit from coal-fired electricity generation by 2040 (referred to as 85/amb/mix/acc.) seems to be promising. In addition to the higher reduction in energy-related CO_2 emissions than in most other scenarios and the political minimum target for 2050, the costs analysis also supports this scenario. At the same time, the installed power of the most important converters of renewable solar and wind energy is in the ranges far below the technical potential limits and in a range, which can most likely be socially accepted. The installed power values for this scenario in 2050 are at 168 GW (onshore wind), 33 GW (offshore wind), 166 GW (photovoltaics), and approx. 159 GW (solar thermal energy for low-temperature heat). For this reason, the development of the technologies and costs should be investigated in more detail in the following for this scenario. At the same time, an energy and CO_2 analysis is carried out for this system in the 2050 configuration.

4.1 2015-2050 System Development

First, the system composition development is presented over time from 2015 to 2050 for the most important components. All presentations in this chapter refer to the scenario with a reduction in energy-related CO_2 emissions by 85 % in 2050.

4.1.1 Electricity generation

The development of the expansion of wind turbines and photovoltaic plants is shown in Fig. 32. A mostly constant increase can be recognised over the entire period. However, it must be observed that we used upper limits for the capacity that can be net-added per year. The detailed data can be found in table 4 in appendix 2.

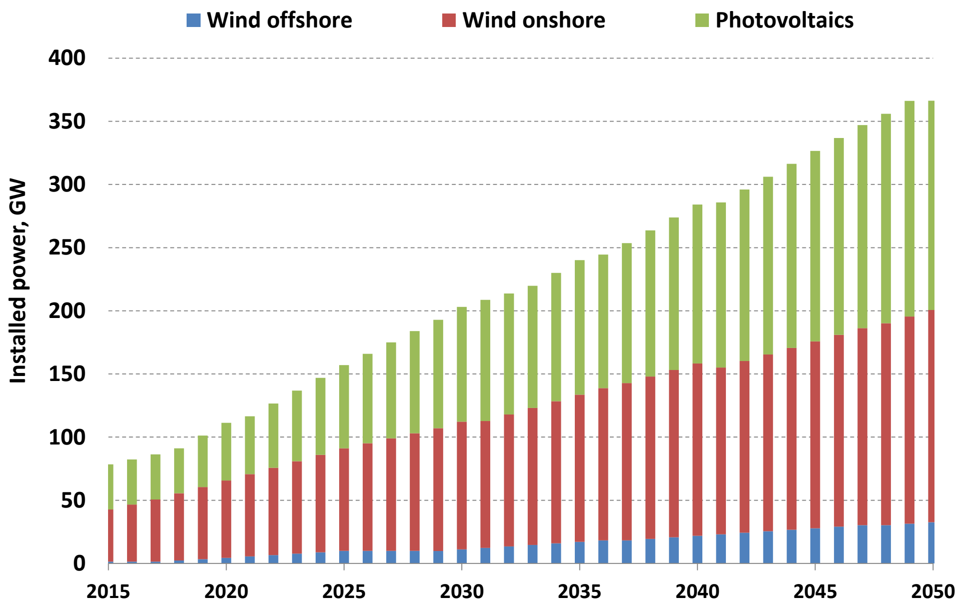


Fig. 32 Profile of the total installed power of wind turbines and photovoltaic plants in the 85-% scenario

The amount installed per year is partly significantly above these limits, as replacement installations become necessary, as presented in Fig. 33. Here can be seen that a first significant amount of replacement installations for onshore wind turbines is required in the 2020s, and a second amount starting in the mid-2030s, and in the last six years from 2044 to 2050. In the case of photovoltaic plants, a respective phase with high replacement installations occurs in the late 2030s and 2040s. Here, the many plants installed in 2010 to 2013 must be replaced.

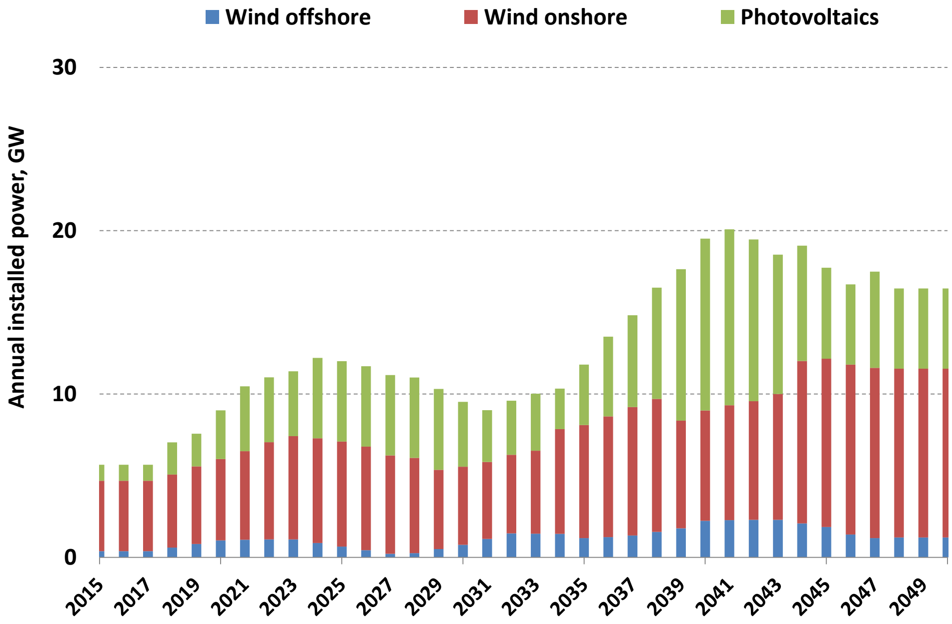


Fig. 33 Profile of the yearly installed gross power (i.e., including replacement installations) of wind turbines and photovoltaic plants.

The installed electric power of thermal power plants and CHP plants decreases overall as shown in Fig. 34. It decreases from more than 100 GW to slightly above 80 GW. A significant shift away from nuclear and coal-fired power plants towards gas turbines and GGCT power plants can be observed.

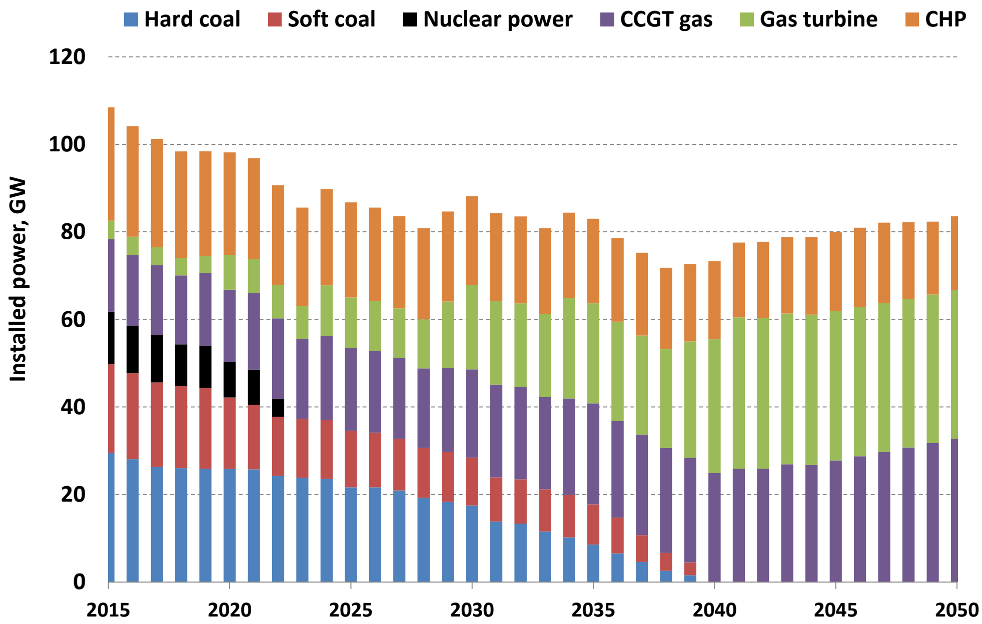


Fig. 34 Profile of the installed power of thermal power plants and/or electrical power of CHP plants.

4.1.2 Heat Supply and Building

Fig. 35 shows the profile of energy renovations of buildings. According to this chart, almost all buildings would be renovated by 2040, while the major share is renovated to the standard of current new constructions and a comparably small share to a highly efficient standard.

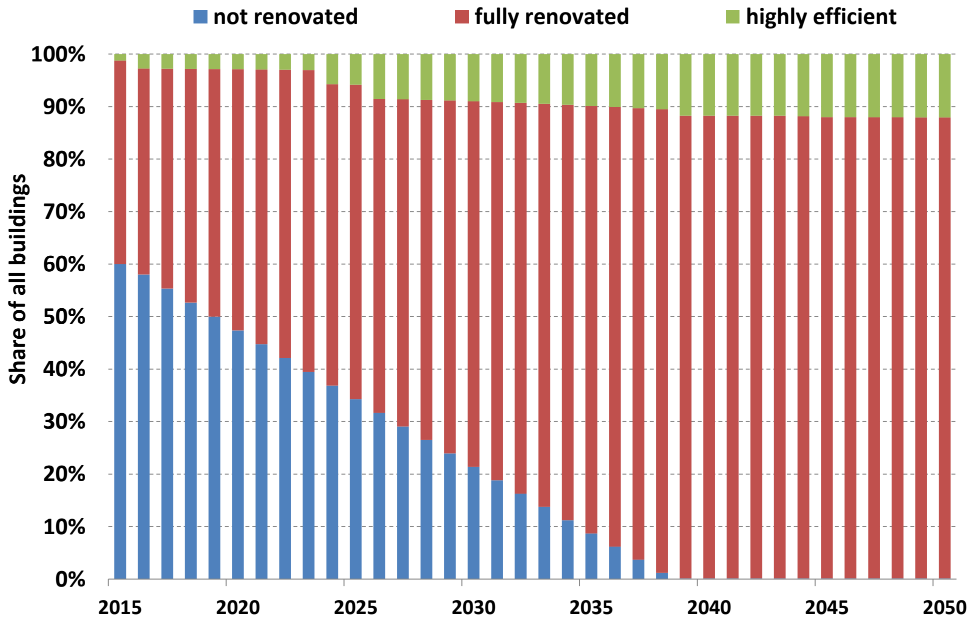


Fig. 35 Development of the renovation status of the building sector.

The composition of heat supply technologies is shown in Fig. 36.

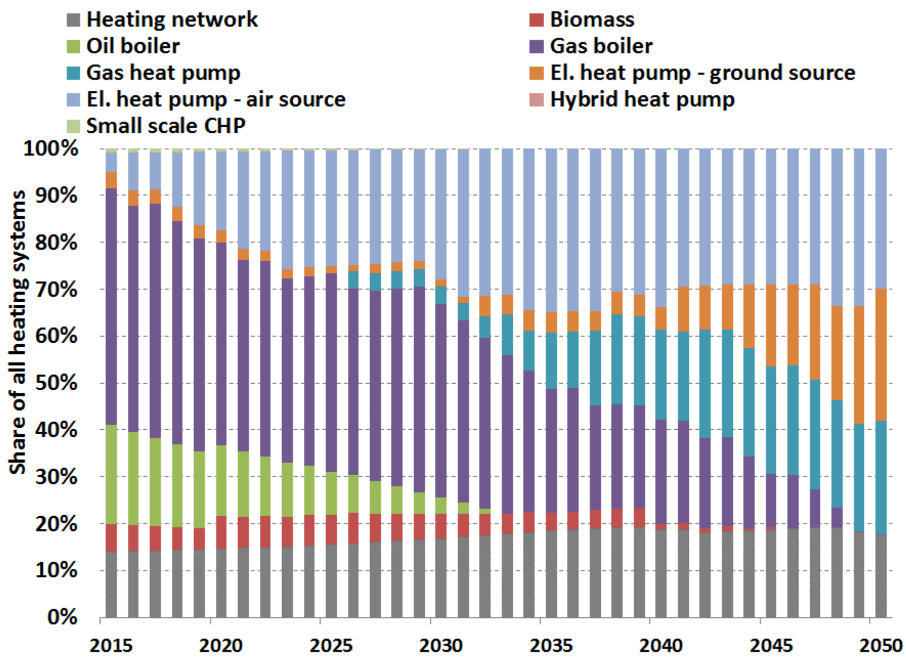


Fig. 36 Development of heat supply technologies in buildings.

The chart highlights that oil boilers expire first, followed by gas boilers. The number of biomass boilers decreases significantly starting from 2040 after a slight increase in the 2020s. Due to the limited available potential, biomass is preferably used in other applications. Heat pumps become the dominating heating technology, with the number of heat pumps with air heat source slightly decreases from the mid-2030s in favor if ground-coupled heat pumps and gas heat pumps. The number of district heat connections increases slightly only and is at approx. 20 % at the end of the investigated period.

Fig. 37 shows the development of the installed power of solar thermal energy plants for low-temperature processes over time.

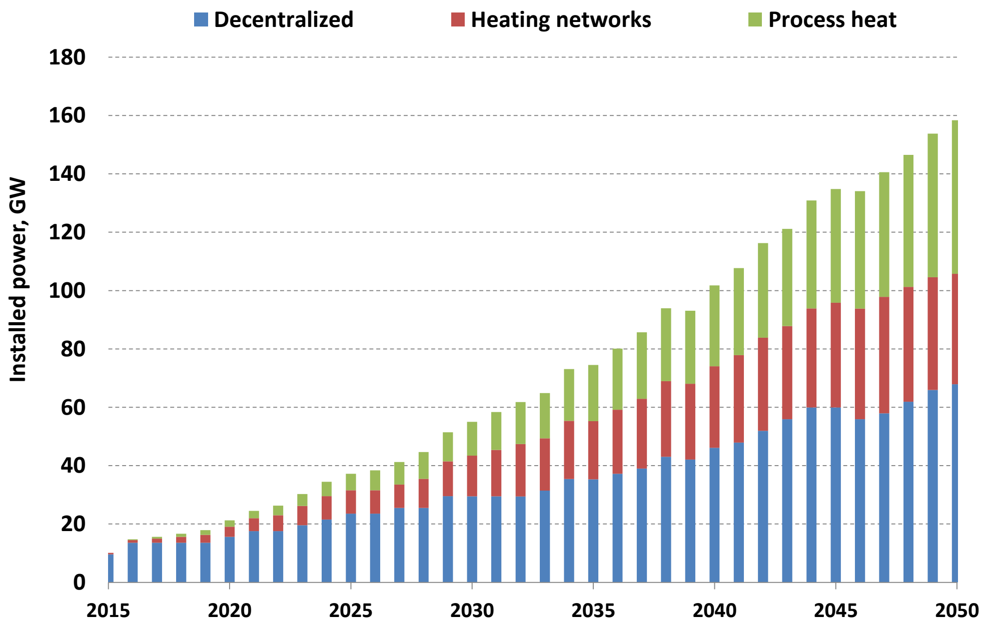


Fig. 37 Development of the installed power of solar thermal energy plants for the provision of low-temperature heat in individual buildings (decentralised), in connection with heating networks, and in trade and industrial processes

4.1.3 Energy Storage and Power-to-Hydrogen/-Gas/-Fuel Technologies

Fig. 38 shows the development of the installed capacity of stationary batteries (in GWh) as well as of converters of renewable energies into synthetic energy carriers (in GW). Fig. 39 shows the development of installed capacity of decentralised and centralised heat storage.

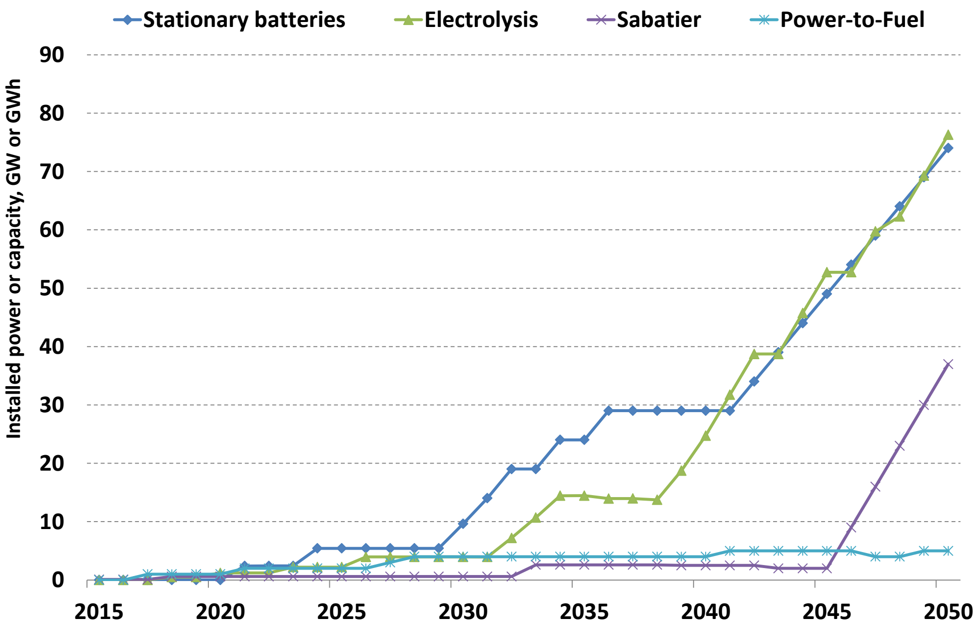


Fig. 38 Development of the installed capacity and/or power of stationary batteries and plants for the conversion of renewable energy (solar, wind) into synthetic energy carriers.

The decreasing availability of fossil fuels on the one hand, and the continuous expansion of fluctuating renewable energies on the other hand cause an increasing demand. Storage enables the chronological adaptation of electricity generation and usage. Converters from renewable energy into synthetic energy carriers enable a flexible electricity use at times of high solar and/or wind power supply and can compensate for decreasing fossil energy carriers. The chart shows that, in the context of the system transformation, short-term storage devices (decentralized heat storage, stationary batteries) are installed first, followed by large heat storage devices in heating networks, electrolyzers, and finally converter units of renewable power into methane (Sabatier systems) that are only required in higher quantities in the last transformation phase (2040s).

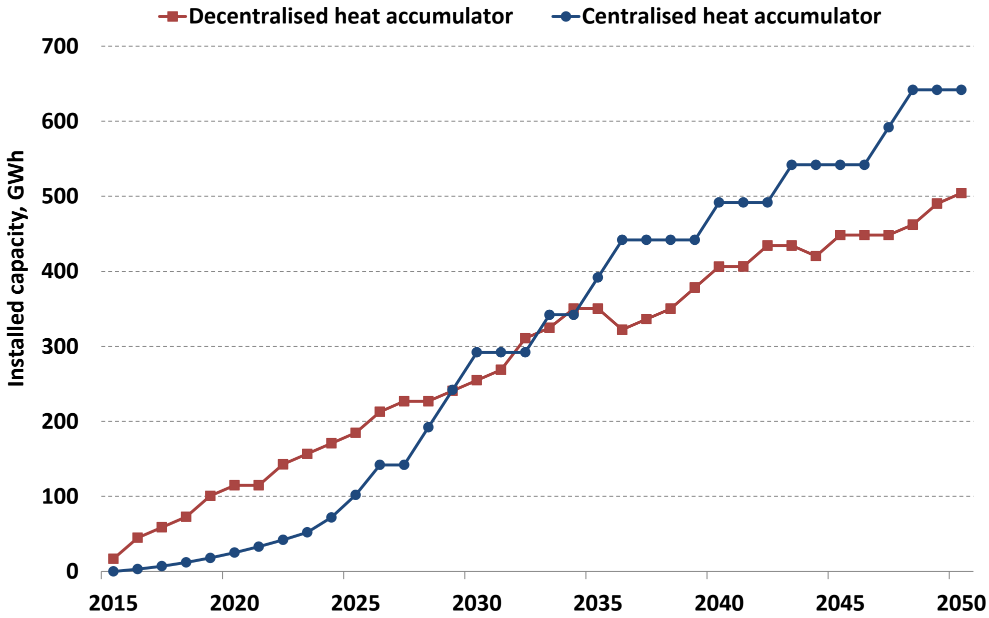


Fig. 39 Development of the installed capacity and/or power of decentralised heat storage and centralised heat storage coupled to heating networks

4.2 2015-2050 Cost Development

The cumulative costs of the investigated scenarios from 2015 to 2050 were presented in chapter 3.2 and compared to the respective costs of the reference system. Fig. 40 shows the chronological profile for the selected scenario with 85 % CO_2 reduction (Fig. 40 top). At the same time, the graph shows the costs for the reference system (Fig. 40 center) and the difference in costs with and without CO_2 emission costs (Fig. 40 bottom). Costs in the amount of €100 per ton CO_2 were assumed as constant value over the entire period. In addition, constant import prices for fossil energy resources were assumed.

As already explained in section 3.2.3, this value – namely € 100 per ton of CO_2 emissions – results over the entire period from 2015 to 2050 in almost the same total costs for the 85-% scenario and the reference case. The difference costs are also close to the zero line throughout the chronological development. Under these conditions, lower fuel costs and the costs for CO_2 emissions compensate for increasing investments (including financing costs), as well as operating and maintenance costs in the 85-% scenario.

A similar chart with a price increase for imported fossil energy resources (natural gas, crude oil, oil products, hard coal) of real 2 % and a CO_2 cost profile according to Fig. 29 is shown in Fig. 41.

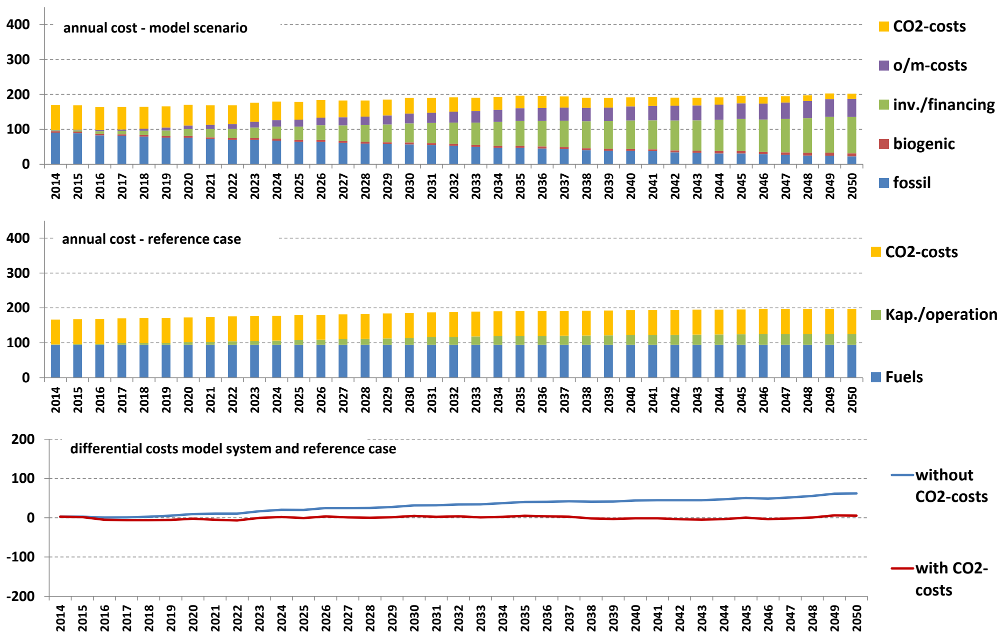


Fig. 40 The chronological cost development for the 85-% scenario (top), the fuel costs as well as CO_2 costs for the reference scenario (center), and the difference costs between model system and reference (bottom) are shown. The chart applies for constant costs of €100 per ton charged for CO_2 emissions.

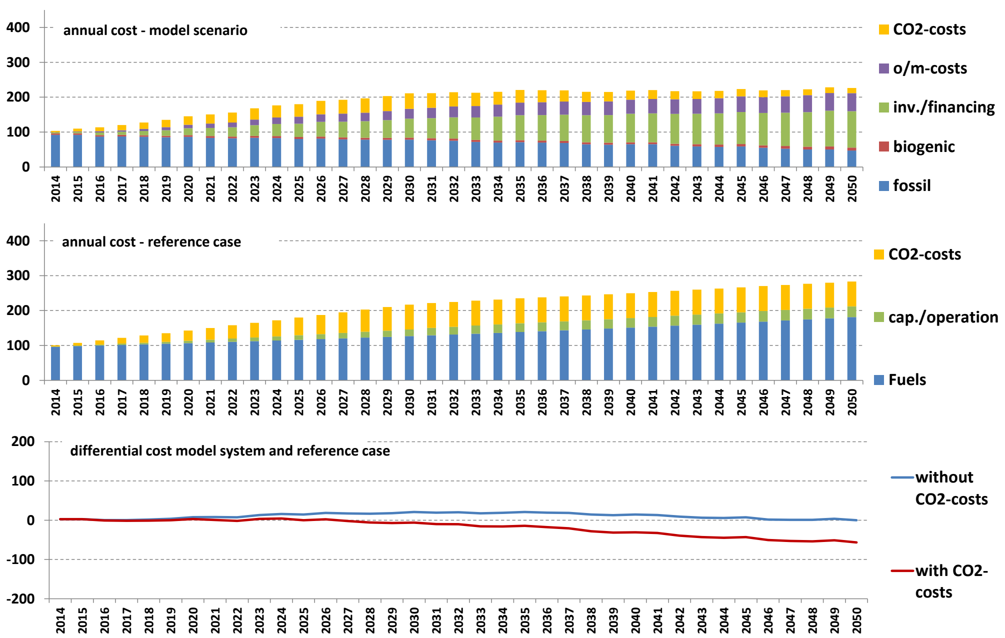


Fig. 41 Same chart as in Fig. 40, however for the following conditions:
- 2 % yearly price increase for the import costs of fossil energies
- CO_2 emission costs according to Fig. 29

Here, the result is continuously increasing costs for both scenarios. In the case of the 85-% scenario, these costs tend to stabilize from the beginning of the 2030s, while the cost increase continuously for the reference scenario due to the increasing costs of imported fossil energy resources. As already explained in section 3.2.3, this results in approx. 8 % lower cumulative total costs for the 85-% scenario than for the reference case for 2015 to 2050 under the given boundary conditions.

4.2.1 Remark Regarding Discounting

The question of discounting of future goods and/or measures at the level of economies is of a dimension far beyond the questions of purely financial-mathematical calculation methods. This is particularly the case when significant effects on the living conditions of future generations must be expected. For example, Dieter Birnbacher writes: »It is increasingly realized that discounting cannot be discussed without reference to ethical questions« [32]. In the same work »Can discounting of the future be justified?«, he presents the various discussions regarding the pros and cons of discounting of future investments in connection with important developments of societies as well as their monetary analysis. The German Federal Environmental Agency suggested in its publication regarding methodological questions for environmental cost estimates [18] the following approach regarding the discount rate selection: »Summarizing, this results in the following convention for the selection of the social discount rate: For short-term periods (up to 20 years), a discount rate of 3 % should be used. For damage extending further into the future, the discount rate is set to a default of 1.5 %. Furthermore, in the case of investigations across generations, a sensitivity calculation with a discount rate in the amount of 0 % is to be carried out.«

For this reason, a discount rate of 3 % was consistently used in the optimisation calculations. This means that there was a tendency to prefer investments taking place further in the future. However, the result presentation has not yet considered any discounting of future costs. Thus, the real costs incurred year by year were used for the calculations. In addition to the above-mentioned general discussion regarding the appropriate discounting rate, this approach is mainly justified by the fact that we have considered the cost development of technologies as well as the influence of cost changes for fossil fuel caused by increasing import prices or costs charged for CO_2-emissions explicitly in our analysis and discussion in chapters 3.2 and 4.2. Nevertheless, the influence of different discounting rates is presented here using the 85-% scenario as example.

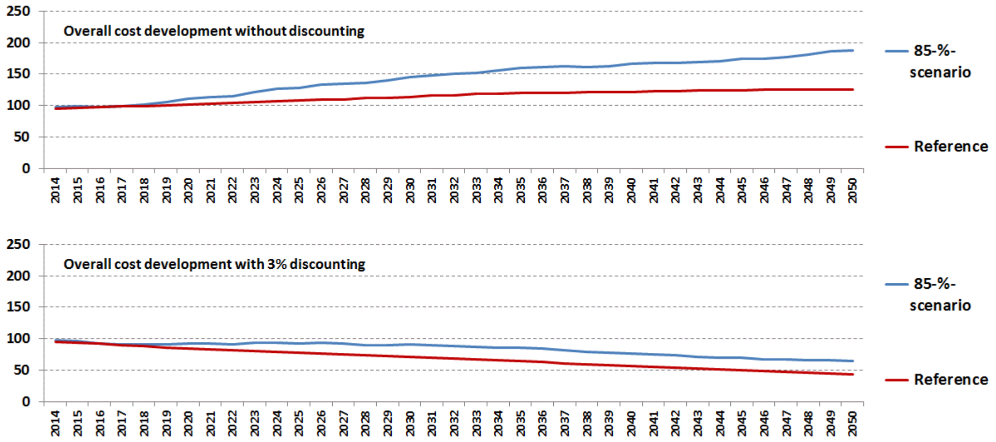


Fig. 42 Total cost development for the 85-% scenario and the reference case without discounting (top) and with discounting at a discount rate of 3 % (bottom). The following conditions apply:
- No price increase for fossil energy carriers
- No CO_2 emission costs

Fig. 42 shows the cost development for the 85-% scenario and the reference case in comparison at a discount rate of 0 % (top) and 3 % (bottom). The profile clearly shows the discounting influence. The result is that the further payments are in the future, the less important they become. In the specific case, discounting at a discount rate of 3 % results in increasing costs turning into decreasing costs. Table 2 shows the cumulative total costs of both scenarios for different discount rates in comparison. The higher the discount rate, the lower the cumulative total costs and the smaller the differences between the compared scenarios.
Having consistent comparability in mind, all further informations in this study are based on an investigation without discounting.

Discount rate	Reference	85-% scenario
0 %	4,212 billion €	5,342 billion €
1 %	3,509 billion €	4,401 billion €
2 %	2,961 billion €	3,671 billion €
3 %	2,529 billion €	3,100 billion €

Tab. 2 Cumulative total costs for the period from 2014 to 2050 for the 85-% scenario and the reference case for different discount rates.

4.3 Total Costs for Operation and Maintenance after Completed Transformation

Until now, the cumulative total costs for the transformation of the energy system until 2050 were investigated starting from the configuration in 2013. If the transformation is considered completed in 2050, no further expansion or retrofit investments are necessary anymore. However, the system must be maintained and operated at the achieved state. Thus, replacement investments, financing costs for these replacement investments, operating and maintenance costs, as well as costs for further used fossil energy carriers and energy carriers from biomass are incurred.

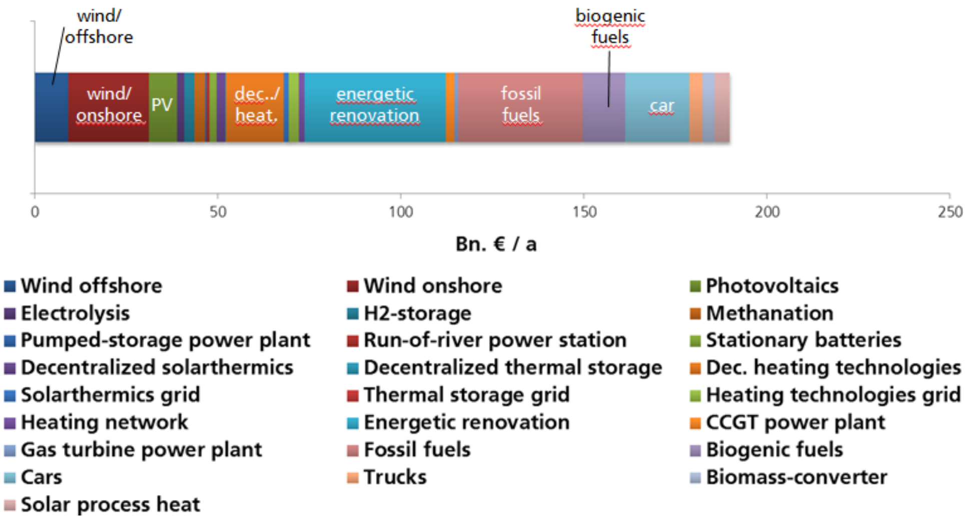


Fig. 43 Composition of the yearly costs of the 85-% system in "steady state", hence after completed system transformation.

Fig. 43 shows the total costs for the 85-% scenario in "steady state". Here, the costs for replacement investments, financing, and operation and maintenance are summarised for all technical components. The costs for fossil fuels are based on the assumption that no real price increase occurs in the period until 2050. The main cost portions result from wind turbines and solar plants for electricity generation, the (additional) costs for decentralised heating technologies (additional costs relative to the gas condensing boiler reference technology), costs for energy renovation of buildings, (additional) costs for the changed composition of the passenger car fleet, and the costs for fossil and biogenic fuels.

A comparison of the yearly total costs for all end consumers for the 85-% system and our current energy system is shown in Fig. 44. Data for the current system was available for 2008 and 2011 [33, 34]. In the presentation of the current system, the costs consist of the costs for domestic and imported primary energy and all other costs included in the end consumer prices. To ensure comparability, a flat amount of 30 % was assumed for taxes and profits for the 85-% system, which is added to the system costs and fuel costs. Different from the presentation for the current system, the system costs also include operating and maintenance costs.

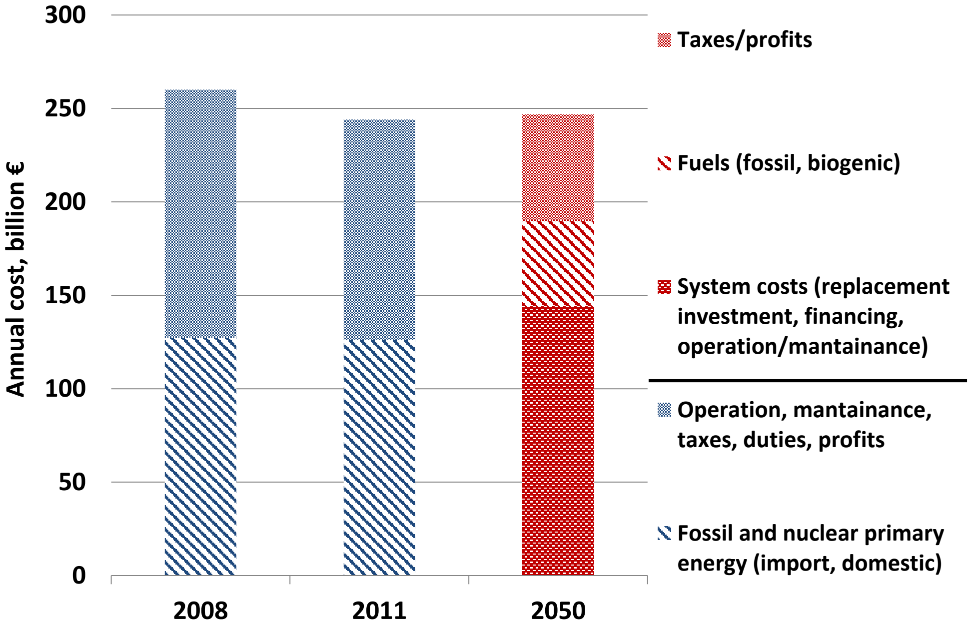


Fig. 44 Comparison of the yearly end consumer costs of the German energy system in 2008 and 2011 (based on data from [33, 34] (left and center bar) and for the investigated system with 85 % CO_2 reduction (right bar).

The result shows that the yearly end consumer costs in the case of the presented system with a reduction in energy-related CO_2 emissions are in a very similar range as the respective values of the current system. It can thus be assumed that a future energy system with significantly reduced CO_2 emissions can also be economically beneficial from a macro-economic point of view after the completed transformation, in particular, if the costs for fossil energy carriers are increasing.

4.4 Energy Balance after Completed Transformation

If the transformation of the energy system considered as completed in 2050, the system is then maintained and operated in the achieved state. This results for this year in the values specified in Fig. 45 for all energy flows and installed powers and/or capacities.

The total primary energy used in the system amounts to approx. 2,050 TWh for the 85-% scenario after transformation completion. It thus amounts to 57 % of today's primary energy supply (without primary energy for non-energetic use). As can be seen in Fig. 46, 67 % originates from renewable sources. Here it must be noted that electricity and heat (including environmental heat) from renewable energies were defined as primary energy (and not the energy arriving at the respective plants, i.e., the energy of wind flow and incident solar radiation). The lower primary energy requirement has two main reasons. On the one hand, the energy renovation of buildings and the assumed reduction in electricity requirements for classic electricity applications and the assumed reduction in the process heat requirement of the industry due to increased efficiency lead to reductions in the consumption. On the other hand, main losses in the conversion chains are omitted. In particular, the losses in the current power plant sector are omitted to a large extent, as only a small portion of electricity is generated in thermal power plants. The changed mix of drive concepts in the area of road mobility also leads to an increase of the portion of concepts with high conversion efficiency and a reduction of the portion of pure combustion engines.

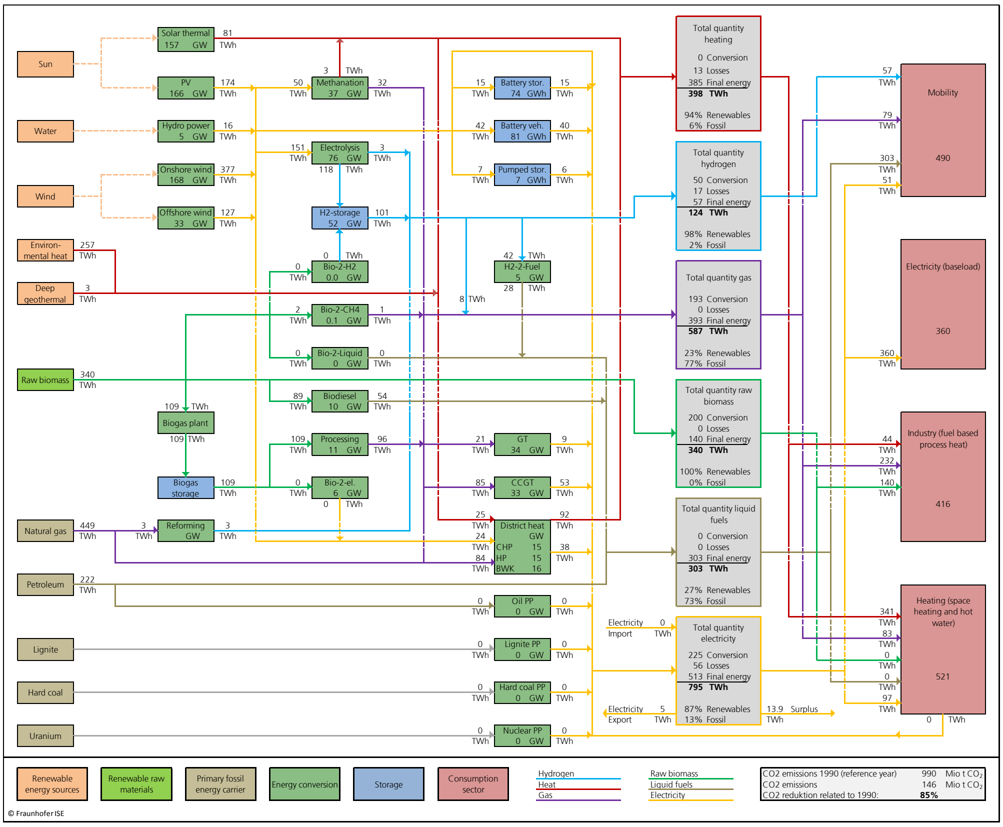


Fig. 45 Energy flows and installed powers of the components of the energy system in 2050 (85-% scenario).

The absolute portions of renewable energies in the primary energy in the 85-% system amount to: photovoltaics 9 %, onshore wind 18 %, offshore wind 6 %, run-of-river 1 %, solar thermal energy 4 %, environmental hear 13 %, raw biomass 16 %.

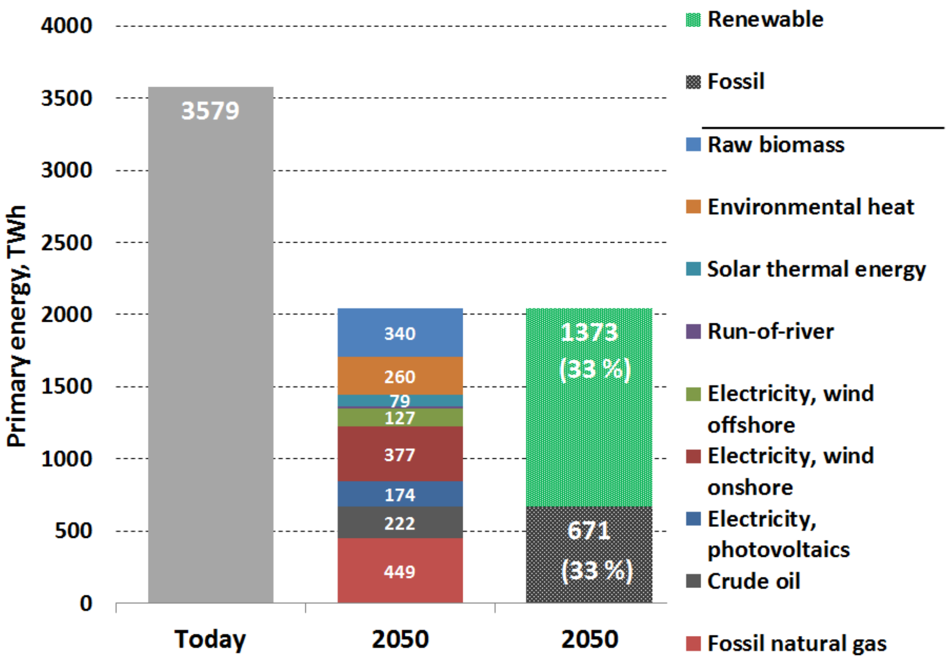


Fig. 46 Primary energy supply and composition in 2050 for the 85-% scenario (center and right bar) in comparison to today's primary energy supply (left bar).

The use of final energy by modified fields of application (definition, see section 2.1) is shown in Fig. 47.

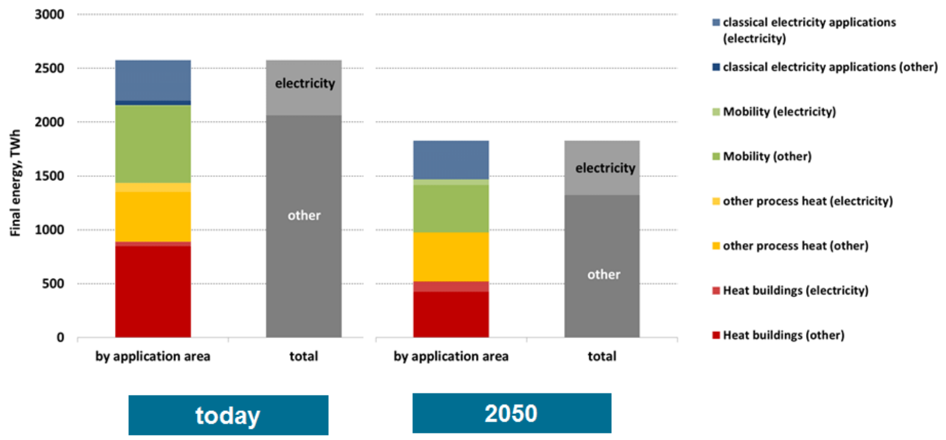


Fig. 47 Final energy distribution to the fields of application defined in section 2.1 today and in 2050 for the 85-% scenario.

Here it becomes clear that the final energy consumption decreases (from today 2,575 TWh to approx. 1,790 TWh, and thus by approx. 30 %). On the one hand, this is due to the reduction in electricity consumption in classic electricity applications, the assumed reduction in the process heat requirement in trade and industry, and the reduction in the space heating requirement due to energy renovation of buildings. On the other hand, this is due to the more efficient use of final energy electricity in the heating area due to the high portion of heat pumps and in electric vehicles in the mobility sector. The relative portion of electricity as final energy increases. However, the absolute amount remains almost the same with approx. 510 TWh.

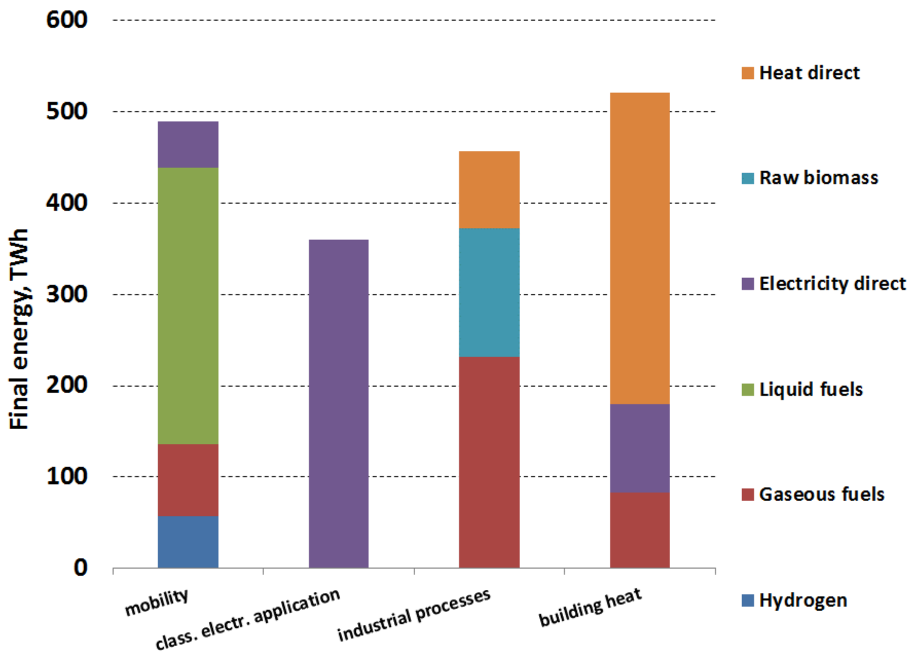


Fig. 48 Distribution of final energy carriers to the fields of application defined in section 2.1 for the 85-% scenario.

Fig. 48 presents the distribution of final energy carriers to the different fields of application defined in section 2.1 for the 85-% system in more detail. It becomes clear that the mobility sector is still dominated by liquid fuels. This is due to the selected mobility scenario for road mobility (»Mix« mobility scenario) and the additional assumption that shipping and aviation are based completely on liquid fuels. In the building sector, directly used heat is of central importance. This includes district heat supplied from different sources, as well as solar heat used in individual buildings. The majority of electricity directly used for heat applications is efficiently converted into useful heat in electric heat pumps. Gaseous fuels are respectively converted in gas heat pumps.

The composition of electricity generation in the 85-% system is shown in Fig. 49 and the composition of the electricity use in Fig. 50. It becomes clear that electricity generation as well as electricity use is higher than today. In 2013, the electricity generation amounted to 633 TWh and the use to 515 TWh. The difference consists of losses and own consumption in the power plant sector (a total of 71 TWh) and net electricity export (around 34 TWh).

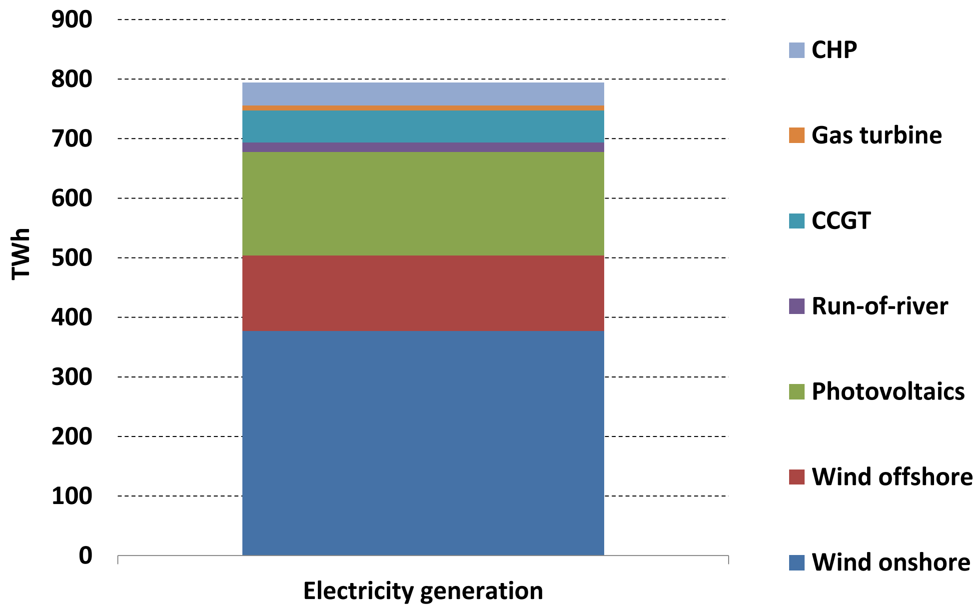


Fig. 49 Composition of electricity generation in the 85-% system.

In the 85-% system, the electricity generation amounts to close to 800 TWh. Of that, approx. 85 % are fluctuating renewable energies (onshore wind 47 %, offshore wind 16 %, and photovoltaics 22 %).

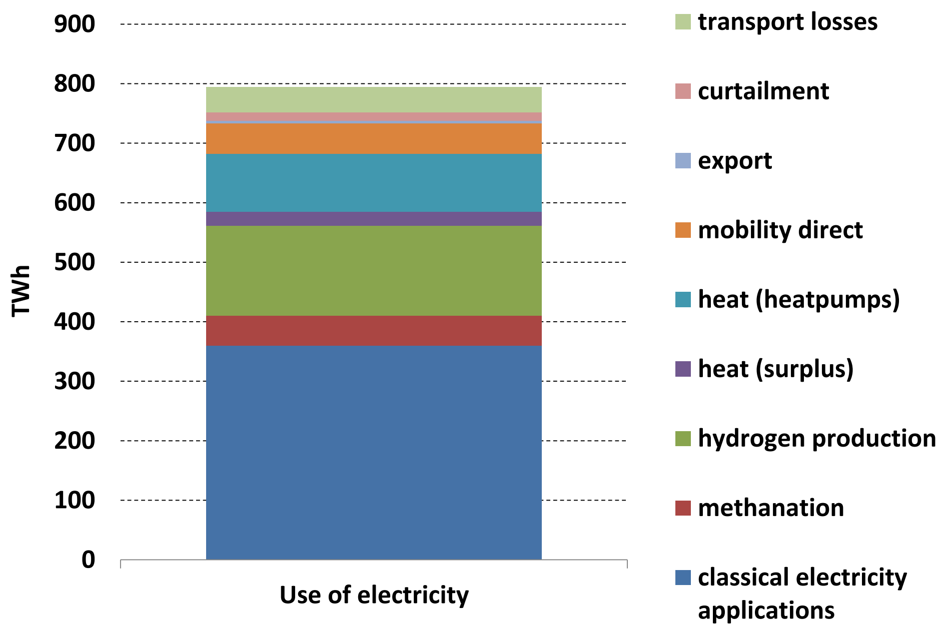


Fig. 50 Composition of electricity use in the 85-% system.

Approx., half of the used electricity in the 85-% system is for classic electricity applications. The other half is distributed to hydrogen production (20 %), electricity for electric heat pumps (13 %), electric mobility with battery-electric motor vehicles (7 %), methanation (7 %), electricity conversion into heat by resistance heaters (3 %), and export (1 %). Excess electricity that cannot be used in the amount of 2 % must be curtailed and 6 % of the generated electricity is lost during transport.

Overall, 733 GWh electricity are used in the system (this value is distributed to the portions shown in Fig. 50 with the exception of transport losses, export, and curtailment). This is approx. 43 % more than today (515 TWh in 2013). The significantly smaller difference between electricity supply and used electricity in 2050 compared to today is mainly caused by the significantly smaller own consumption in the power plant sector.

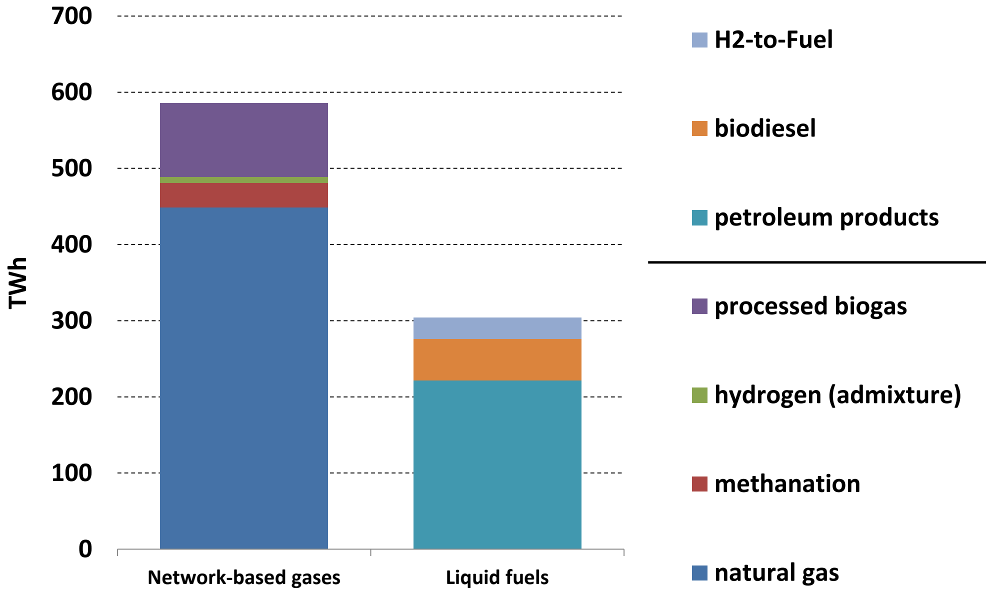


Fig. 51 Composition of the origin of network-bound gases (left bar) and liquid fuels (right bar) in the 85-% system.

In the 85-% system, 587 TWh network-bound gaseous energy carriers are used. They consist to 76 % of natural gas and to 24 % of different gaseous energy carriers that originate from renewable sources. These are biogas refined to natural gas quality (17 %), methane from Sabatier systems (5 %), and hydrogen that is added to natural gas (1 %). The composition of the network-bound gaseous energy carriers is indicated by the left bar in Fig. 51.

The amount of liquid fuels used in the 85-% system amounts to 303 TWh. The composition is shown by the right bar in Fig. 51. The quantity is distributed to 73 % to oil products, 18 % to biodiesel, and 9 % to synthetic liquid fuels produced with electricity from renewable energies (power-to-liquid).

4.5 Importance of Electricity Import and Electricity Export

Potentially, electricity import and export possibilities can be of significantly higher importance in the future energy system than today. For example, if not enough renewable electricity is available from solar energy and wind, electricity could be imported from neighboring countries. In times of negative residual loads, electricity could be exported. This way, storage capacities in Alpine countries and in Scandinavia could be developed as well. However, the development of the possible scope of electricity import and export depends decisively form the development of the electricity supply of neighboring countries and Europe. In the case of a strong expansion of renewable energies for electricity generation based on solar energy and wind, the result will be similar chronological profiles in directly neighboring countries for regenerative electricity generation, as general weather situations decisively influence the profile. In this respect, the long-term development of the chronological profile of the electricity price for sales and purchasing also depends decisively on the expansion of the electricity supply in Europe.

Due to the uncertainty in the development of electricity generation in Europe, we have assumed in the calculations presented so far that import and export are of no significant importance and that the capacity for electricity import and export is limited to 5 GW, as described in section 2.2.3. However, in order to gain some understanding regarding the influence of a large-area electricity exchange with neighboring countries on the system development despite the problem described above, we have carried out a respective optimisation calculation for the 85-% scenario. Here, electricity import and export are of high priority as a total coupling power of 56 GW was assumed [19]. Today's total coupling power amounts to 15 GW. With respect to the development of the exchange power, we have assumed a linear increase from 15 GW today to 56 GW in 2050. Furthermore, the following was assumed for electricity import and export:

- Purchase price for electricity import remains constant from 2015 to 2050: 80 €/MWh.
- Revenue for electricity export remains constant from 2015 to 2050: 0 €/MWh.
- Specific CO_2 emissions for imported electricity: 0 g/kWh. This value is obviously incorrect and unrealistic for 2050. However, we selected this value to investigate an extreme scenario.

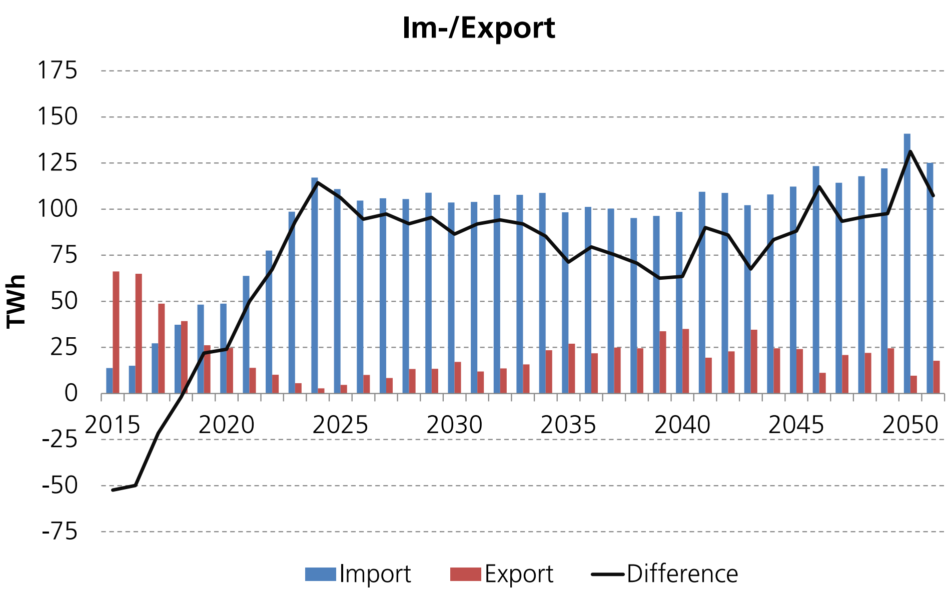


Fig. 52 Electricity import and electricity export and the difference in the modified 85-% scenario (source: [8]).

Fig. 52 shows the profile of electricity import and export for the investigated period in this modified 85-% scenario. At the same time, the net import is presented, i.e., the difference of both values. While the result is an export excess in the first few years, this changes into an import excess after a short time. At the beginning of the 2020s, this excess amounts to values between approx. 75 TWh per year and 125 TWh per year. In 2050, the electricity import value is approx. 125 TWh and thus at approx. 16 % of the overall electricity supply. Approx. 18 TWh or 2 % of the used electricity is exported in this year. The chronological profile of the installed power of wind energy systems and photovoltaics in the modified 85-% scenario is shown in Fig. 53. This figure can be directly compared with Fig. 32 in section 4.1.1. It can be seen that the expansion is largely identical, despite the high possible import power for electricity from abroad.

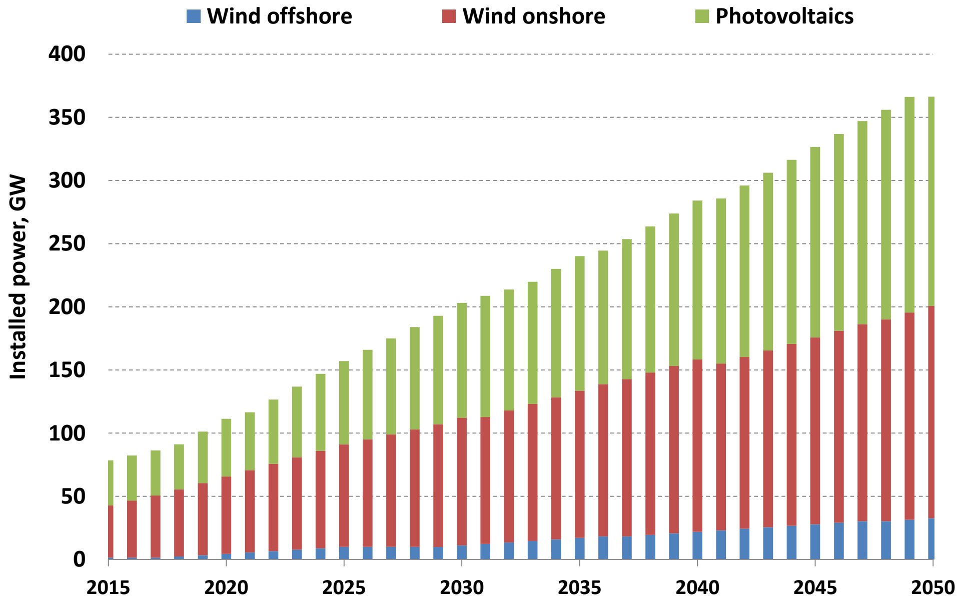


Fig. 53 Development of the installed power of electricity supply systems based on solar energy and wind for the modified 85-% scenario. The chart can be compared with the respective development for the 85-% scenario without high capacity for electricity import and export (Fig. 32).

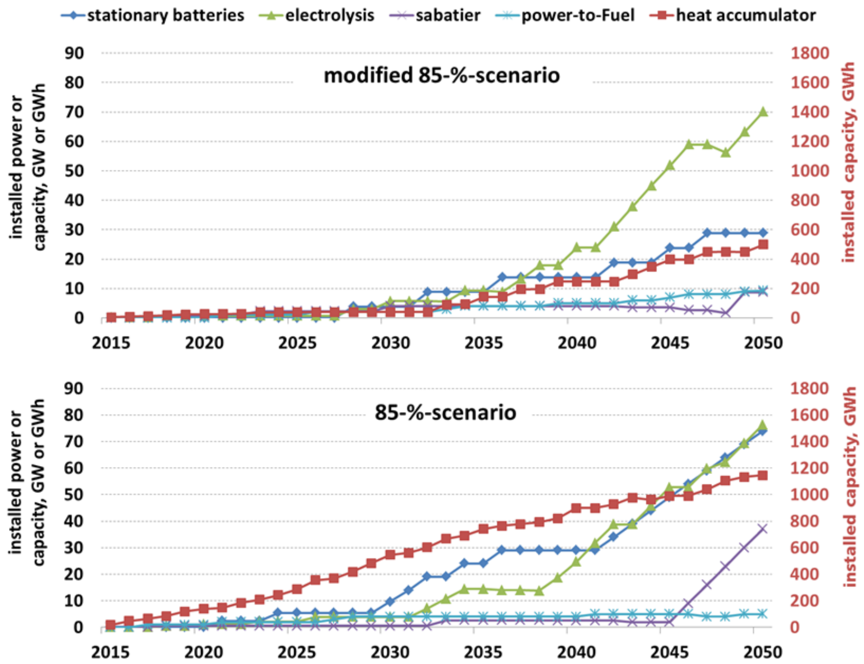


Fig. 54 Development of the installed capacity and/or power of storage and converters of renewable electricity into synthetic energy carriers in the modified 85-% scenario with increased capacity for electricity import and export (top) and for the 85-% scenario without increased capacity for electricity import and export (bottom).

However, due to the possible electricity import and export, the result is fewer installations of energy storage and converters of renewable electricity into synthetic energy carriers (see Fig. 54) as in the respective 85-% scenario without increased capacity for electricity import and export. A respective chart is presented for the 85-% scenario without increased electricity import and export for comparison purposes. The values for decentralised and centralised heat storage were combined into a total value for this purpose.

At the same time, it can be seen that the increased electricity import and export capacity does not only lead to an overall lower value, but also to a later storage expansion (stationary batteries, heat storage). Merely the profile of electrolysis system expansions is more or less similar. Here, the demand is caused by the increasing portion of motor vehicles that use fuel cells with electric motors as drive concept. This development was defined through the »Mix« mobility scenario specified for the 85-% scenario. The expansion of plants for the generation of liquid fuels (power-to-fuel) and gaseous energy carriers (Sabatier) cannot be completely omitted either in the scenario with increased electricity import and expert, as respective fuels are required for the mobility and heat sectors.

Under the assumptions made here, the modified 85-% scenario would lead to lower cumulative total costs than the previously investigated scenario without increased capacity for electricity import and export. Assuming that the prices for fossil energy carriers remained the same and without costs charged for CO_2 emissions, the cumulative total costs for the latter were approx. €5,350 billion. The respective value for the modified 85-% scenario amounts to approx. €4,800 billion. With a constant price for imported electricity of real 80 €/MWh, the import costs for electricity are lower than the total costs for a greater expansion of energy storage and conversion of renewable energies into synthetic energy carriers. However, it must be considered that we assumed the extreme investigation that imported electricity does not contribute to CO_2 emissions.

On the one hand, the analysis of the modified 85-% scenario shows that the expansion of solar- and wind-based electricity generation plants – even under very optimistic assumptions for the CO_2 content of imported electricity and assuming that this electricity is always available in the required amount – is required regardless of the possible capacity of electricity imports and exports to not exceed the specified maximum quantities of permissible CO_2 emissions. On the other hand, the analysis shows that the expansion of storage and converters of renewable electricity into synthetic energy carriers can be smaller if a larger option for electricity import and exports is given.

4.6 Summary of the Investigation of the 85-% Scenario

The detailed analysis of the 85-% scenario and of the system achieved with this scenario in 2050 delivers the following findings:

- Compared to today (reference year 2013), the primary energy supply reduced by approx. 43 % to approx. 2,050 TWh. Of that, 57 % are renewable energy carriers. Here, electricity and heat from renewable energies were defined as primary energy.

- The installed power of plants for the use of fluctuating renewable energies for electricity generation amounts to a total of 367 GW. Of that, 166 GW are photovoltaics, 168 GW onshore wind, and 33 GW offshore wind.

- The final energy requirement reduces by 30 % relative to the current value and amounts to 1,790 TWh. On the one hand, the reduced requirement is due to the reduction in electricity consumption in classic electricity applications and the reduction in requirements for space heating due to energy renovation of buildings. On the other hand, it is due to the more efficient use of final energy electricity in the heating sector due to the high portion of heat pumps and in the mobility sector in the electric vehicles.

- The cumulative additional costs for the transformation compared to the investigation of the reference case with unchanged further operation of the system in today's configuration amounts to approx. €1,140 billion or 27 %

relative to the reference case. This value assumes no price increases for fossil energy carriers and no costs charged for CO_2 emissions.

- The cost situation changes to the degree by which price increases occur for fossil energy carriers and/or costs are charged for CO_2 emissions. For example, if we assume a price increase for imported fossil energy carriers of 20 % per year and a linear increase of the costs charged for CO_2 emissions to 100 € in 2030, which then remain at this value until 2050, the cumulative total costs of the 85-% scenario are approx. 600 billion € (or 8 %) below the comparable costs of the reference case.

- If the system present in 2050 investigated as »steady-state« system, i.e., the transformation is considered completed, the result is total costs in a very similar range as the respective values today, namely approx. €250 billion per year. This statement applies under the assumption that the prices for fossil energy carriers remain unchanged until 2050 and that no costs are charged for CO_2 emissions.

5 Summary

From today’s perspective, the efficient conversion and use of energy as well as the use of renewable energies are the central components of the transformation of current energy systems that are mainly based on the use of fossil energy resources towards energy systems with significantly lower CO_2 emissions. Quantitative values for required powers and capacities of important energy converters and storage as well as of plant on the usage side can be derived from our analysis, which lead to such system solutions in line with climate protection. It becomes clear that the required quantities for all important converters of renewable energies, in particular from wind and solar energy, are significantly below the technical potential limits. The scenario investigated in detail with a reduction in energy-related CO_2 emissions by 85 % requires installed power values of 33 GW for offshore wind turbines, 168 GW for onshore wind turbines, as well as 166 GW for photovoltaic systems and approx. 160 GW for solar thermal energy systems. At the same time, this scenario implies an ambitious energy renovation of the building stock and a high portion of heat pumps for building heating. Due to a significantly higher conversion efficiency in the overall system – in particular also due to the displacement of today’s thermal power plants by renewable energies, and due to the partial displacement of combustion processes by electric or partly electric converters on the usage side – connected with a reduction in consumption mainly in the building sector and in intrinsic (classic) electricity applications, the primary energy supply for energy applications decreases significantly to approx. 60 % of today’s value. Approx. 60 % of this supply is covered by renewable energies.

The comparison of the investigated scenarios shows that an electrification of road mobility, an accelerated energy renovation (however, not to the passive house level), and, in particular, an accelerated exit from the use of coal for electricity generation lead to lower installed powers of solar energy systems and wind turbines and more cost-effective transformation pathways than respective transformation pathways without these measures. As, in today’s point of view, the implementation of these measures is particularly in the mobility sector still highly uncertain, we decided to investigate a scenario with a mix of different mobility concepts in more detail. This scenario implies a reduction in energy-related CO_2 emissions by 85 %. If a reduction of energy-related CO_2 emissions by 90 % instead, a tipping point is observed in the system expansion when comparing these two systems. The 90-% target requires a significantly higher quantity of wind turbines and solar energy systems and a significantly more extensive renovation of the building sector. At the same time, the heat supply sector for individual building uses almost exclusively electric heat pumps. This scenario also requires significantly more plants for the production of synthetic fuels from renewable energies. The comparison of these two systems highlights the importance of defining target values to start the new construction and/or expansion of respective infrastructures on time and to achieve a respectively high efficiency standard during energy renovation of buildings with a long life.

Another import result concerns the question of economic implementation of the energy system transformation. Decarbonising the German energy supply is not a self-propelling economic success. Significant investments in the transformation are required to achieve the political climate protection targets overall and along the timeline. This transformation comprises energy sector and – more or less – all consumption sectors. In this context, investments are required from different parties involved, from the public sector as well as from commercial, institutional, and private investors. These investments in plants and other measures, such as energy renovation measures, also cause operating and maintenance costs. Financing costs are incurred as well. All these additional financial expenditures are offset by continuously increasing savings resulting from the continuous decrease in the quantity of imported fossil energy resources.

The investigation of nine different climate protection scenarios shows that the cumulative total costs for transformation and operation of the overall energy supply system over the investigated period from 2015 to 2050 of the most cost-effective climate protection scenarios are higher than the costs of a reference scenario, where the energy system remains unchanged at the 2014 status until 2050. This statement is correct if the prices for imported fossil energy resources remain constant and no costs are charged for CO_2 emissions. Under these conditions, the cumulative additional costs of the investigated 85-% scenario amount to approx. €1,100 billion compared to the reference scenario. If these additional costs are equally distributed from 2014 - 2050, the result is yearly additional costs of approx. €30 billion, which corresponds to approx. 0.8 % of the German gross domestic product in 2013.

The situation regarding the cumulative total costs changes to the degree by which the costs for fossil energy carriers increase. This may be caused by increasing world market prices or by costs charged for CO_2 emissions, such as emission certificates or CO_2 taxes. The cumulative total costs of the 85-% scenario that achieves in 2050 a reduction of energy-related CO_2 emissions of 85 % (compared to 1990), are approx. 8 % lower than the costs for the reference scenario. This assumes a yearly increase of real 2 % of the prices for fossil energy carriers and a continuously increasing CO_2 fee that increases to 100 € per ton CO_2 by 2030 and remains at this value until 2050. This value of 100 € per ton would increase the price of natural gas by approx. 2.1 € Cent per kWh and of hard coal by approx. 3.4 € Cent per kWh.

Another aspect concerns external energy supply costs. Except in the investigations regarding the effect of costs charged for CO_2 emissions, external costs were not considered in our entire analysis. A detailed quantitative analysis would be possible based on the quantity structures resulting from our analyses for the investigated climate protection scenarios. Here, at this point, a qualitative statement is possible only: considering external costs, e.g., resulting from environmental effects due to the reduction of fossil fuels (e.g., lignite coal), would very likely increase the costs of the investigated reference system – i.e., of an unchanged further operation of our energy system in the current form – significantly more than a retrofitted energy system that is mainly based on renewable energies.

The new calculations confirm our results of the study published in November 2013. According to that study, the yearly costs of an overall system in line with climate protection after completed energy system transformation are not higher than the respective costs of our current energy system. These costs comprise replacement investments, financing costs, operating and maintenance costs, and consumption costs for fossil and biogenic energy resources, as well as taxes and profits.

When analysing the results of our study, it must be pointed out that the analysis of the energy system was carried out independently from the economy. A comprehensive economic investigation with complete added value analyses would provide insight regarding economic effects that would be triggered by the transformation of the energy system. The following qualitative statement can be made here: depending on the technology and/or measure, certain portions of the retrofit and expansion investments will lead to added value in Germany in the course of the energy system transformation, even if the basic components are imported for some technologies. Plant installation will always take place on site, which will contribute to added value, respectively. The same applies to plant operation and maintenance, which is also carried out on site. In contrast, only a small extent of local added value is lost due to the continuously decreasing import of fossil energy carriers, e.g., due to the lower demand for the conversion of crude oil into different oil products.

6 Bibliography

[1] UBA: *Emissionen von Luftschadstoffen*. URL http://www.umweltbundesamt.de/themen/luft/emissionen-von-luftschadstoffen – Überprüfungsdatum 2015-09-22

[2] BUNDESMINISTERIUM FÜR WIRTSCHAFT UND TECHNOLOGIE: *Die Energiewende in Deutschland. Mit sicherer, bezahlbarer und umweltschonender Energie ins Jahr 2050*. 2012

[3] EUROPEAN COMMISION: *Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions* : *A Roadmap for moving to a competitive low carbon economy in 2050*. Brussels, 2011

[4] EU-COMMISSION: *The 2020 climate and energy package* – Überprüfungsdatum 2015-02-17

[5] HENNING, Hans-Martin ; PALZER, Andreas: *100 % ERNEUERBARE ENERGIEN FÜR STROM UND WÄRME IN DEUTSCHLAND*. Freiburg, 11.2012

[6] HENNING, Hans-Martin ; PALZER, Andreas: *ENERGIESYSTEM DEUTSCHLAND 2050* : *Sektor- und Energieträgerübergreifende, modellbasierte, ganzheitliche Untersuchung zur langfristigen Reduktion energiebedingter CO2-Emissionen durch Energieeffizienz und den Einsatz Erneuerbarer Energien*. Freiburg, 11.2013

[7] BMWI: *Zahlen und Fakten. Energiedaten. Nationale und internationale Entwicklung* – Überprüfungsdatum 2015-09-22

[8] PALZER, Andreas: *Sektorübergreifende Modellierung und Optimierung eines zukünftigen deutschen Energiesystems unter Berücksichtigung von Energieeffizienzmaßnahmen im Gebäudesektor*. Karlsruhe, Karlsruher Institut für Technologie. (eingereichte) Dissertation. 2016-04-28

[9] TROST, Tobias ; HORN, Sönke ; JENTSCH, Mareike ; STERNER, Michael: *Erneuerbares Methan: Analyse der CO2-Potenziale für Power-to-Gas Anlagen in Deutschland*. In: *Zeitschrift für Energiewirtschaft* 36 (2012), Nr. 3, S. 173–190 – Überprüfungsdatum 2015-03-17

[10] DWD: *CDC - Climate Data Center*. URL http://www.dwd.de/cdc – Überprüfungsdatum 2015-03-18

[11] DWD: *Veröffentlichungen zum COSMO-Modell (COSMO-EU, COSMO-DE, COSMO-DE EPS)*. URL www.dwd.de – Überprüfungsdatum 2015-03-18

[12] AGORA: *Current and Future Cost of Photovoltaics* : *Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems*. 2015

[13] KAH, Oliver ; FEIST, Wolfgang: *Wirtschaftlichkeit von Wärmedämm - Maßnahmen im Gebäudebestand 2005*. Darmstadt, Mai 2005

[14] PILLEN, Nicole ; DISCHER, Henning ; HINZ, Eberhard ; ENSELING, Andreas: *Bericht 2010. dena-Sanierungsstudie. Teil 1* : *Wirtschaftlichkeit energetischer Modernisierung im Mietwohnungsbestand. Begleitforschung zum dena-Projekt „Niedrigenergiehaus im Bestand“*. 2010

[15] STOLTE, Christian ; MARCINEK, Heike ; DISCHER, Henning ; HINZ, Eberhard ; ENSELING, Andreas: *Bericht 2011. dena-Sanierungsstudie. Teil 2* : *Wirtschaftlichkeit energetischer Modernisierung in selbstgenutzten Wohngebäuden. Begleitforschung zum dena-Projekt „Niedrigenergiehaus im Bestand“*. Berlin, 2012

[16] BÜRGER, Veit ; HESSE, Tilmann ; PALZER, Andreas ; HERKEL, Sebastian ; ENGELMANN, Peter: *Klimaneutraler Gebäudebestand 2050*. aktuell in Bearbeitung. Dessau - Roßlau, 2015. – aktuell in Bearbeitung

[17] FEIST, Wolfgang: *EnerPHit und EnerPHio+i – Zertifizierungskriterien für die Modernisierung mit Passivhaus-Komponenten*. URL http://www.passiv.de/de/03_zertifizierung/02_zertifizierung_gebaeude/04_enerphit/04_enerphit.htm – Überprüfungsdatum 2015-03-19

[18] UMWELTBUNDESAMT (UBA): *Ökonomische Bewertung von Umweltschäden* : *METHODENKONVENTION 2.0 ZUR SCHÄTZUNG VON UMWELTKOSTEN*. Dessau - Roßlau, August 2012

[19] UMWELTBUNDESAMT: *Treibhausgasneutrales Deutschland im Jahr 2050*. Dessau - Roßlau, 2014

[20] SCHLESINGER, Michael ; LINDENBERGER, Dietmar ; LUTZ, Christian: *Entwicklung der Energiemärkte - Energiereferenzprognose*. 2014

[21] ZIESING, Hans-Joachim: *Klimaschutzszenario 2050 1. Modellierungsrunde*. Berlin, 2014

[22] BUNDESMINISTERIUM FÜR VERKEHR, BAU UND STADTENTWICKLUNG: *Szenarien der Mobilitätsentwicklung unter Berücksichtigung von Siedlungsstrukturen bis 2050*. Magdeburg, 2006

[23] ENTSOE. URL https://www.entsoe.eu/data/data-portal/Pages/default.aspx. – Aktualisierungsdatum: 2012-08-27 – Überprüfungsdatum 2015-03-19

[24] BNETZA: *Kraftwerksliste*. URL http://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Versorgungssicherheit/Erzeugungskapazitaeten/Kraftwerksliste/kraftwerksliste-node.html. – Aktualisierungsdatum: 2014-10-29 – Überprüfungsdatum 2015-03-04

[25] EEX: *Generation on the previous day* – Überprüfungsdatum 2012-08-20

[26] VERBAND DER ELEKTROTECHNIK ELEKTRONIK INFORMATIONSTECHNIK E.V.: *Energiespeicher in Stromversorgungssystemen mit hohem Anteil erneuerbarer Energieträger - Bedeutung, Stand der Technik, Handlungsbedarf*. 2008

[27] INSTITUT FÜR ELEKTRISCHE ANLAGEN UND ENERGIEWIRTSCHAFT, VOITH HYDRO GMBH & CO. KG: *Die Energiewende erfolgreich gestalten: Mit Pumpspeicherkraftwerken*. 2014

[28] NETZENTWICKLUNGSPLAN: *Szenariorahmen für die Netzentwicklungspläne Strom 2015* : *Entwurf der Übertragungsnetzbetreiber*. 2014

[29] UMWELTBUNDESAMT: *Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-Protokoll 2014* : *Nationaler Inventarbericht zum Deutschen Treibhausgasinventar 1990 - 2012*. Dessau-Roßlau, 07.2014

[30] KIRCHNER, A. ; MATTHES, F. C.: *Endbericht Modell Deutschland – Klimaschutz bis 2050: Vom Ziel her denken*. Basel/Berlin, 2009

[31] HAAS, Karin ; HECKING, Claus: *"Wir müssen in den nächsten 25 bis 30 Jahren aussteigen"* : *Bundesumweltministerin Barbara Hendricks kündigt das Ende der Kohlekraftwerke an – und spricht über atomare Altlasten.* In: *DIE ZEIT* 2015 (2015-07-26), Nr. 28

[32] BIRNBACHER, Dieter ; BRUDERMÜLLER, Gerd: *Zukunftsverantwortung und Generationensolidarität* : *(Schriftenreihe des Instituts für angewandte Ethik e.V.)*. Würzburg : Königshausen & Neumann GmbH, 2001

[33] BUNDESMINISTERIUM FÜR WIRTSCHAFT UND TECHNOLOGIE: *Energie in Deutschland* : *Trends und Hintergründe zur Energieversorgung*. 2010

[34] BUNDESMINISTERIUM FÜR WIRTSCHAFT UND TECHNOLOGIE: *Energie in Deutschland* : *Trends und Hintergründe zur Energieversorgung*. 2013

[35] INTERNATIONAL ENERGY AGENCY: *Energy technology perspectives 2012. Pathways to a Clean Energy System*. 2012

[36] REUTER, Andreas: *Wind On-/Offshore* : *Stromgestehungskosten für 2050*. 2014

[37] INTERNATIONAL ENERGY AGENCY: *Technology Roadmap* : *Bioenergy for Heat and Power*. Paris, 2012

[38] HOBOHM, Jens ; KRAMPE, Leonard ; PETER, Frank ; GERNKEN, Andree ; HEINRICH, Peter ; RICHTER, Maik: *Kostensenkungspotenziale der Offshore - Windenergie in Deutschland*. Berlin, 2013

[39] KOST, Christoph ; MAYER, Johannes N. ; THOMSEN, Jessica ; HARTMANN, Niklas ; SENKPIEL, Charlotte ; PHILIPPS, Simon ; NOLD, Sebastian ; LUDE, Simon ; SCHLEGL, Thomas: *Stromgestehungskosten Erneuerbare Energien*. 2013

[40] NITSCH, Joachim ; PREGGER, Yvonne ; NAEGLER, Tobias ; STERNER, Michael ; GERHARDT, Norman ; OEHSEN, Amany von ; PAPE, Carsten ; SAINT-DRENAN, Yves-Marie: *Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global „Leitstudie 2010"*. 2010

[41] MAYER, Johannes N.: *Current and Future Cost of Photovoltaics* : *Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems*. 02.2015

[42] INTERNATIONAL ENERGY AGENCY: *Energy technology perspectives 2010. Scenarios & stragegies to 2050*. 2010

[43] JAGER, David de ; KLESSMANN, Corinna ; STRICKER, Eva ; WINKEL, Thomas ; VISSER, Erika de ; KOPER, MICHELE, RAGWITZ, MARIO ; HELD, Anne ; RESCH, Gustav ; BUSCH, Sebastian ; PANZER, Christian ; GAZZO, Alexis ; ROULLEAU, Thomas ; GOUSSELAND, Pierre ; HERNIET, Marion: *Financing Renewable Energy in the European Energy Market. Final report*. 2011

[44] DEUTSCHE ENERGIE-AGENTUR GMBH: *dena-Netzstudie I – Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore bis zum Jahr 2020*. 2005

[45] BUNDESMINISTERIUM FÜR WIRTSCHAFT UND TECHNOLOGIE: *Energietechniken 2050 - Schwerpunkte für Forschung und Entwicklung. Politikbericht*. 2010

[46] ASUE ARBEITSGEMEINSCHAFT FÜR SPARSAMEN UND UMWELTFREUNDLICHEN ENERGIEVERBRAUCH E.V.: *BHKW - Kenndaten 2011* : *Module Anbieter Kosten*. Frankfurt a. M., 2011

[47] GANTEFORT, Wilhelm: *Beurteilung von Biogasanlagen mit Vergärung von nachwachsenden Rohstoffen und realistische Kalkulation von Gaserträgern*. Heiden, 2006

[48] WEIDNER, Eckard: *FG Biomasse* : *Stromgestehungskosten 2050*. Schriftenreihe Energiesysteme der Zukunft. Veröffentlichung wird Ende 2015 erwartet. – Schriftenreihe Energiesysteme der Zukunft

[49] FNR: *Faustzahlen Biogas*. URL http://biogas.fnr.de/daten-und-fakten/faustzahlen/ – Überprüfungsdatum 2015-02-10

[50] ALBRECHT, Uwe ; ALTMANN, Matthias ; MICHALKSI, Jan ; RAKSHA ; TETYANA ; WEINDORF, Werner: *Analyse der Kosten Erneuerbarer Gase* : *Eine Studie der Ludwig-Bölkow-Systemtechnik GmbH*. 2013

[51] ZECH, Konstantin ; GRASEMANN, Elias ; OEHMICHEN, Katja ; KIENDL, Isabel ; SCHMERSAHL, Ralf ; RÖNSCH, Stefan ; WEINDORF, Werner ; FUNKE, Simon ; MICHAELIS, Julia ; WIETSCHEL, Martin ; SEIFFERT, Michael ; MÜLLER-LANGER, Franziska: *Hy-NOW Evaluierung der Verfahren und Technologien für die Bereitstellung von Wasserstoff auf Basis von Biomasse*. 2013

[52] KARL, Jürgen ; KIENBERGER, Thomas ; KRÖNER, Martin: *Auf dem Holzweg*. Methangasgewinnung. In: *Erneuerbare Energien - Das Magazin* (2010) – Überprüfungsdatum 2015-03-23

[53] JENSEN, Dierk: *Effizienzsteigerung im Fermenter*. In: *VDI Nachrichten* (2014), Nr. 19. URL http://www.vdi-nachrichten.com/Technik-Wirtschaft/Effizienzsteigerung-im-Fermenter – Überprüfungsdatum 2015-03-23

[54] BUNDEMINISTERIUM FÜR BILDUNG UND FORSCHUNG: *Abschlussbericht für das BMBF - Verbundprojekt "Biogaseinspeisung" : Beseitigung technischer, rechtlicher und ökonomischer Hemmnisse bei der Einspeisung biogener Gase in das Erdgasnetz zur Reduzierung klimarelevanter Emissionen durch Aufbau und Anwendung einer georeferenzierten Datenbank*. Band 3 Synthesegasmethanisierung. Verfahrenstechnische und ökonomische Analyse thermochemischer Gaserzeugungs - und Aufbereitungsverfahren. 2009. – Band 3 Synthesegasmethanisierung. Verfahrenstechnische und ökonomische Analyse thermochemischer Gaserzeugungs - und Aufbereitungsverfahren

[55] DEUTSCHES BIOMASSEFORSCHUNGSZENTRUM: *Bioenergie heute und morgen - 11 Bereitstellungskonzepte*. Sonderheft zum DBFZ Report. Leipzig, 2011. – Sonderheft zum DBFZ Report

[56] WIESE, Lars: *Energetische, exergetische und ökonomische Evaluierung der thermochemischen Vergasung zur Stromerzeugung aus Biomasse*. Hamburg, TU Hamburg Harburg. Dissertation. 2007. URL https://www.deutsche-digitale-bibliothek.de/binary/BJJYKPUXC7OYN3RYEFR7ULI7FSLTQCF4/full/1.pdf – Überprüfungsdatum 2015-02-10

[57] BECKMANN, Michael (Hrsg.); KLEMM, Marco (Hrsg.): *Strategien der energetischen Biomassenutzung* : TK Verlag Tomé- Kozmiensky, 2008

[58] HENNING, H.-M. ; RAGWITZ, M. ; BÜRGER, V. ; JOCHEM, E. ; KRANZL, L. ; SCHULT, W.: *Erarbeitung einer Integrierten Wärme- und Kältestrategie* : *Arbeitspaket 1 - Bestandsaufnahme und Strukturierung des Wärme- und Kältebereichs*. 2012

[59] FIRRISA, Melese Tesfaye ; VAN DUREN, Iris ; VOINOV, Alexey: *Energy efficiency for rapseed biodiesel production in different farming systems*. In: *Energy Efficiency* (2013). URL http://www.likbez.com/BE/10.1007_s12053-013-9201-2.pdf – Überprüfungsdatum 2015-02-10

[60] LAMBAUER, J. ; FAHL, U. ; OHL, M. ; BLESL, M. ; VOß, A.: *Industrielle Großwärmepumpen - Poteziale, Hemmnisse und Best - Practise Beispiele*. 2008

[61] KREWITT, Wolfram ; NIENHAUS, Kristina ; KLEßMANN, Corinna ; CAPONE, Carolin ; STRICKER, Eva ; GRAUS, Wina ; HOOGWIJK, Monique: *Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply. Summary*. Dessau-Roßlau, 2009

[62] SDH: *Ranking List of European Large Scale Solar Heating Plants*. URL http://www.solar-district-heating.eu/ServicesTools/Plantdatabase.aspx – Überprüfungsdatum 2015-03-24

[63] MAUTHNER, Franz: *Task 52 - Solar Heat and Energy Economics in Urban Environments*. Bern, 2014 – Überprüfungsdatum 2015-03-23

[64] HUMMEL: *Subtask A : Vienna University of Technology Energy Economics Group (EEG)*. 2nd Expert Meeting of Task 52. 2nd Expert Meeting of Task 52. 2014 – Überprüfungsdatum 2015-02-10

[65] NITSCH, Joachim ; PREGGER, Thomas ; NAEGLER, Tobias ; HEIDE, Dominik ; LUCA DE TENA, DIEGO ; TRIEB, Franz ; SCHOLZ, Yvonne: *Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global*. 2012 (BMU - FKZ 03MAP146)

[66] KOCK, Nils ; KALTSCHMITT, Martin: *Wärmenutzung bei geothermischen KWK - Anlagen* : *Technische Optionen und deren Bewertung*. In: *VDI - Berichte Nummer 2167* (2012) – Überprüfungsdatum 2015-02-11

[67] WEIMANN, Thorsten: *Vorbereitung und Begleitung der Erstellung des Erfahrungsberichtes 2011 gemäß § 65 EEG* : *im Auftrag des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit Vorhaben IIb (Geothermie) Endbericht*. 2011

[68] ZEITLER, Rolf ; STOCKERL, Thomas: *Geothermieprojekt der Stadt Unterschleißheim*. In: *Dialog Geothermie Unterscheissheim* (2010), Nr. 1. URL http://www.unterschleissheim.de/gtu-geothermie-unterschleissheim-ag.html – Überprüfungsdatum 2015-03-24

[69] *Geowärme Erding*

[70] EWG: *Geothermie sichert umweltfreundliche Wärmeversorgung*. URL http://www.ewg-garching.de/das-projekt/konzept/ – Überprüfungsdatum 2015-03-24

[71] BAYERNWERK: *Sichere und effiziente Strom- und Erdgasnetze für Bayern*. URL https://www.bayernwerk.de/cps/rde/xchg/bayernwerk – Überprüfungsdatum 2015-03-24

[72] GEOTHERMIE PULLACH: *Info-Veranstaltung*. Pullach, 2010 – Überprüfungsdatum 2015-03-24

[73] GEOTHERMIE UNTERHACHING: *Daten & Fakten: Geothermie Unterhaching*. URL https://www.geothermie-unterhaching.de/cms/geothermie/web.nsf/id/pa_daten_fakten.html – Überprüfungsdatum 2015-03-24

[74] FÜREDER, Josef: *Geothermie Braunau-Simbach*. o.J.

[75] EXORKA: *Geothermie – Wärme aus der Erde*. URL http://exorka.de/de/was-ist-geothermie – Überprüfungsdatum 2015-03-24

[76] WIETSCHEL, Martin ; ARENS, Marlene ; DÖTSCH, Christian ; HERKEL, Sebastian ; KREWITT, Wolfram ; MARKEWITZ, Peter ; MÖST, Dominik ; SCHEUFEN, Martin: *Energietechnologien 2050 - Schwerpunkte für Forschung und Entwicklung* : Fraunhofer Verlag, 2010

[77] ERDMANN, Georg ; DITTMAR, Lars: *Technologische und energiepolitische Bewertung der Perspektiven von Kraft-Wärme-Kopplung in Deutschlandand*. Berlin, 2010

[78] MATHES, DR. FELIX CHR. MATTHES ; HARTHAN, Ralph ; LORECK, Charlotte: *Schneller Ausstieg aus der Kernenergie in Deutschland. Kurzfristige Ersatzoptionen, Strom- und CO2-Preiseffekte Kurzanalyse für die Umweltstiftung WWF Deutschland*. Berlin, 2011

[79] FAHL, Ulrich ; BLESL, Markus ; VOß, Alfred ; ACHTEN, Patrick ; BRUCHOF, David ; GÖTZ, Birgit ; HUNDT, Matthias ; KEMPE, Stefan: *Die Entwicklung der Energiemärkte bis 2030 Energieprognose 2009*. 2010

[80] ADAMEK, Franziska ; AUNDRUP, Thomas ; GLAUNSINGER, Wolfgang ; KLEIMAIER, Martin ; LANDINGER, Hubert ; LEUTHOLD, Matthias ; LUNZ, Benedikt ; MOSER, Albert ; PAPE, Carsten ; PLUNTKE, Helge: *Energiespeicher für die Energiewende* : *Sanierungsbedarf und Auswirkungen auf das Übertragungsnetz für Szenarien bis 2050*. 2012

[81] LUNZ, Benedikt: *Elektrochemische Speicher -Lithium-Ionen-Batterien*. 2014

[82] HARTMANN, Niklas ; ELTROP, Ludger ; BAUER, Nikolaus ; SALZER, Johannes ; SCHWARZ, Simon ; SCHMIDT, Maike: *Stromspeicherpotenziale für Deutschland*. 2012

[83] BUSSAR, Christian ; MOOS, Melchior ; ALVAREZ, Ricardo ; WOLF, Philipp ; THIEN, Tjark ; CHEN, Hengsi ; CAI, Zhuang ; LEUTHOLD, Matthias ; SAUER, Dirk Uwe ; MOSER, Albert: *Optimal Allocation and Capacity of Energy Storage Systems in a Future European Power System with 100% Renewable Energy Generation*. In: *Energy Procedia* 46 (2014), S. 40–47 – Überprüfungsdatum 2015-02-16

[84] SAUER, Dirk Uwe: *FG Speicher* : *Kennzahlen für 2050*. 2015

[85] STERNER, Michael: *Bioenergy and renewable power methane in integrated 100% renewable energy systems. Limiting global warming by transforming energy systems*. Kassel, Universität. Dissertation. 2009 – Überprüfungsdatum 2015-03-18

[86] MITTELBACH, Martin: *Methanolgewinnung aus Biogas* : *Machbarkeits - Studie*. Graz, 2005

[87] PEHNT, Martin: *Ganzheitliche Bilanzierung von Brennstoffzellen in der Energie- und Verkehrstechnik*. Stuttgart, Universität Stuttgart, Institut für Technische Thermodynamik (DLR) und Institut für Energiewirtschaft und Rationelle Energieverwendung. Dissertation. 2001-12-14. URL http://www.ifeu.de/energie/pdf/dissertation_pehnt.pdf – Überprüfungsdatum 2015-02-10

[88] MÜLLER, Karsten ; FABISCH, Florian ; ARLT, Wolfgang: *Energy Transport and Storage using Methanol as a Carrier*. In: *Green* (2014), S. 19–25 – Überprüfungsdatum 2015-03-23

[89] BOLLE, Friedrich-Wilhelm ; GENZOWSKY, Kristoffer ; GREDIGK-HOFFMANN, Sylvia ; REINDERS, Michael ; RIßE, Henry: *Einsatz der Wasserstofftechnologie in der Abwasserbeseitigung - Phase I* : *Band I: Kompendium Wasserstoff*. Aachen, 2012

[90] CHEMPARK: *Air Liquide plant Reformer im CHEMPARK Dormagen*. URL http://www.chempark.de/de/air-liquide-plant-reformer-im-chempark-dormagen.html – Überprüfungsdatum 2015-02-10

[91] ROSTRUP-NIELSEN, Thomas: *High Flux Steam Reforming*. Haldor Topsoe A/S, Lyngby, Denmark, o.J.

[92] RUTHARDT, Klaus ; RADTKE, KArsten Rick ; LARSEN, John: *Hydrogen Trends*. 2005

[93] WINTER-MADSEN, Sandra ; OLSSON, Henrik: *Steam reforming solutions*. 2007

[94] BUNDESMINISTERIUM FÜR VERKERH, BAU UND STADTENTWICKLUNG (BMVBS): *Kosten erngierelevanter Bau- und Anlagenteile bei der energetischen Modernisierung von Wohngebäuden*. 2012 (07/2012)

[95] DESTATIS: *Baupreisindizes: Deutschland, Jahre, Messzahlen mit/ohne Umsatzsteuer, Gebäudearten, Bauarbeiten (Hochbau)*. URL https://www.govdata.de/web/guest/daten/-/details/destatis-service--1320123620 – Überprüfungsdatum 2015-02-12

[96] INSTITUT WOHNEN UND UMWELT: *Untersuchung zur weiteren Verschärfung der energetischen Anforderungen an Wohngebäude mit der EnEV 2012* : *Teil 1 -*

Kosten energierelevante Bau- und Anlagenteile in der energetischen Modernisierung von Altbauten. Darmstadt, 2009

[97] ERNST, Christina: *Abschlussbericht. Projekt. Modernisierung von Vorwärmeanlagen (Kesseleinlagen) in Gasdruckregel- und Messanlagen unter Berücksichtigung der Energieeffizienz und alternativer Konzepte*. 2011

[98] LUCAS, K., GEBHARDT, M. ; KOHL, H. ; STEINRÖTTER, Th.: *Ableitung von Kostenfunktionen für Komponenten der rationellen Energienutzung*. Duisburg - Rheinhausen, 2002

[99] RECKNAGEL, Hermann ; SPRENGER, Eberhard ; SCHRAMEK, Eberhard: *Taschenbuch für Heizung und Klimatechnik*. 75. Auflage. München : Oldenburg Industrieverlag, 2012

[100] BUNDESMINISTERIUM FÜR VERKERH, BAU UND STADTENTWICKLUNG: *Ermittlung von spezifischen Kosten energiesparender Bauteil-, Beleuchtungs-, Heizungs- und Klimatechnikausführungen bei Nichtwohngebäuden für die Wirtschaftlichkeitsuntersuchungen zur EnEV 2012*. 2012

[101] KEVAG (Hrsg.): *Sole-Wasser-Wärmepumpe*. 2006

[102] SÄCHSISCHE ENERGIEAGENTUR GMBH: *Wärmepumpen Heizen mit Wärme aus der Umwelt*. Dresden, 2009

[103] NITSCH, Joachim ; KREWITT, Wolfram ; NAST, Michael ; TRIEB, Franz ; SCHMID, Stephan ; KLANN, Uwe ; VIEBAHN, Peter: *Erneuerbare Energien Innovationen für die Zukunft*. 5. Aufl. Mai 2004

[104] SCHULZ, Wolfgang: *Mittel- und langfristige Perspektiven der Technologie-entwicklung für die Wärmeversorgung des Gebäudesektors*. Berlin, 2013 – Überprüfungsdatum 2015-03-23

[105] TGA FACHPLANER: *Verkaufsstart der Zeolith - Gas - Wärmepumpe*. URL http://www.tga-fachplaner.de/Newsarchiv/2010/3/Verkaufsstart-der-Zeolith-Gas-Waermepumpe,QUlEPTI3NTE3NSZNSUQ9MTA3OTg3.html – Überprüfungsdatum 2015-02-10

[106] KALTSCHMITT, Martin ; STREICHER, Wolfgang ; WIESE, Andreas: *Erneuerbare Energien* : *Systemtechnik, Wirtschaftlichkeit, Umweltaspekte*. 5. Aufl. : Springer Vieweg, 2012

[107] KASA, Heli: *SO-PRO – Solar Process Heat Solarthermie in industriellen Prozessen* : *Ein Projekt im Rahmen des Programms „Intelligente Energie – Europa“*. 08.06.2010

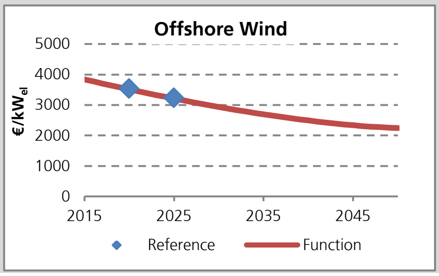
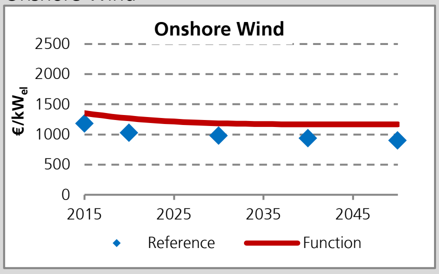
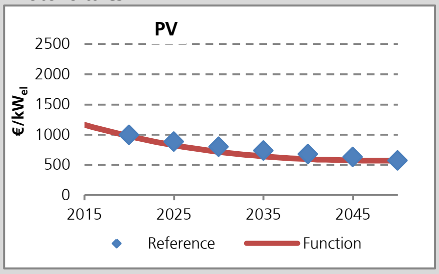
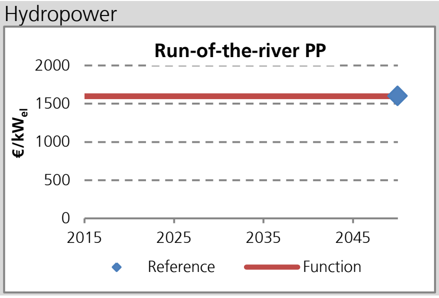
[108] LAMSFUß, Friedrich: *Cofely macht mehr aus ihrer Energie* : *Ihr Partner in Effizienz in Technik und Service*. 2010. URL Cofely macht mehr aus Ihrer Energie" bei SO-PRO-Workshop 2010 – Überprüfungsdatum 2015-02-11

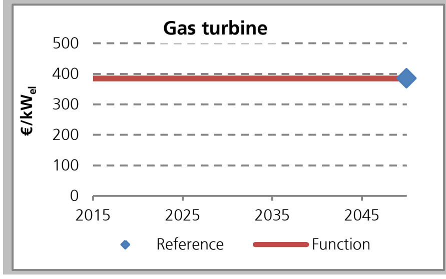
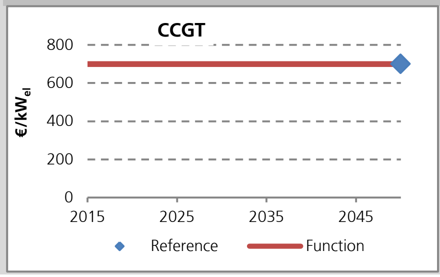
[109] NATIONALE ORGANISATION WASSERSTOFF-UND BRENNSTOFFZELLENTECHNOLOGIE: *Ein Portfolio von Antriebssystemen für Europa: Eine faktenbasierte Analyse* : *Die Rolle von batteriebetriebenen Elektrofahrzeugen, Plug-in Hybridfahrzeugen und Brennstoffzellenfahrzeugen*. 2013

[110] CROTOGINO, Fritz: *Wasserstoffspeicherung im geologischen Untergrund - Stand der Technik und Potential*. Hannover, 2011. URL http://www.kbbnet.de/wp-content/uploads/2011/05/201111_K%C3%B6ln_Cro-Wasserstoffspeicherung-im-geol-Untergrund.pdf – Überprüfungsdatum 2015-02-11

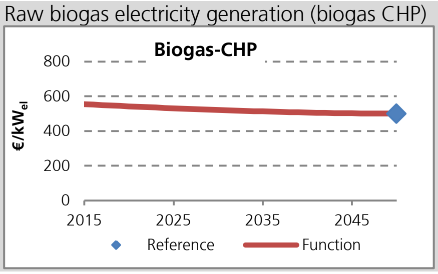
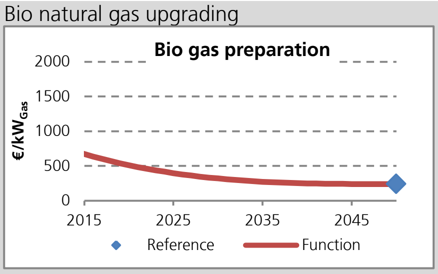
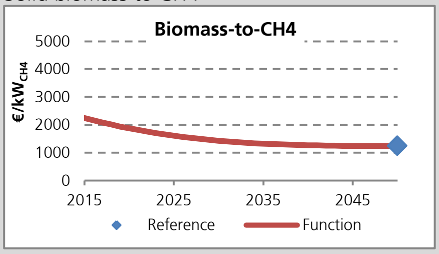
Appendix 1: Data assumptions

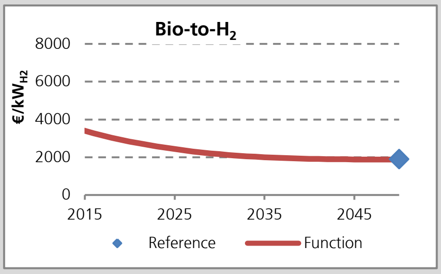
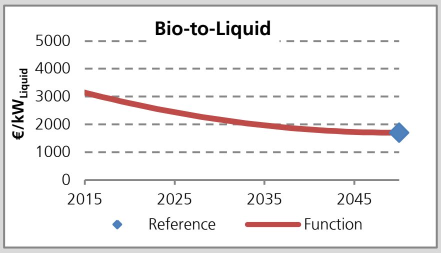
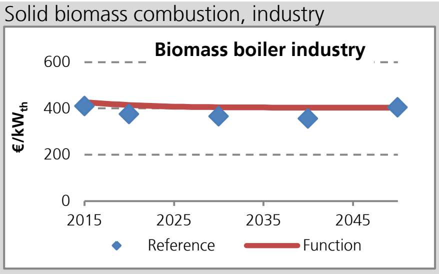
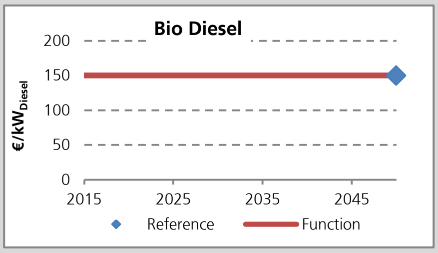
Table 3: Indicators used for components (the K-exponent describes the curve profile)

Electricity generation (without biomass)				
Component	**Variable**	**Unit**	**Value**	**Sources**
Offshore Wind	Costs 2013	€/kW	3978	[35]; [36]
	Costs 2050	€/kW	2251	[35]; [36, 37]
	K-exponent	-	1.5	Based on [38]
	Service life	a	20	[35]; [36]
	Full load hours	h	4000	Own assumptions based on [38]
	M/O costs	% investment	3.03	[35]; [36]
	Calc. interest	%	7	Own assumptions
Onshore Wind	Costs 2013	€/kW	1400	[39]
	Costs 2050	€/kW	1167	[35];[36]; [39]
	K-exponent	-	4	Based on [40]
	Service life	a	22.5	[35]; [37][36], [36]
	Full load hours	h	2500-2000	Own assumptions based on [39]
	M/O costs	% investment	3.4	[35]; [36]
	Calc. interest	%	7	Own assumptions
Photovoltaics	Costs 2013	€/kW	1254	[35]; [12]
	Costs 2050	€/kW	571	[12]
	K-exponent	-	2.5	Based on [12]
	Service life	a	30	[35][37][36][12];
	Full load hours	h	1100-915	Own assumptions based on [41]
	M/O costs	% investment	1.96	[35]
	Calc. interest	%	7	Own assumptions
Hydropower	Costs 2013	€/kW	1,600	[42]
	Costs 2050	€/kW	1,600	[42]
	K-exponent	-	1	Own assumptions
	Service life	a	50	[43]
	M/O costs	% investment	2	[42][42][42]
	Calc. interest	%	7	Own assumptions

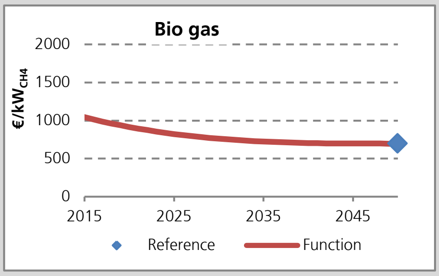
Component	Variable	Unit	Value	Sources
Gas turbine	Costs 2013	€/kW	385	[35]
	Costs 2050	€/kW	385	[35]
	K-exponent	-	1	Own assumptions
	Service life	a	50	Own assumptions
	M/O costs	% investment	2	[35]
	Degree of efficiency	%	42	[35]
	Calc. interest	%	7	Own assumptions
Combined cycle power plant	Costs 2013	€/kW	700	[40]; expert survey
	Costs 2050	€/kW	700	[40]; expert survey
	K-exponent	-	1	Own assumptions
	Service life	a	40	[44]; expert survey
	M/O costs	% investment	3	[44]
	Degree of efficiency	%	63.5	[45]; expert survey
	Calc. interest	%	7	Own assumptions

Biomass

Component	Variable	Unit	Value	Sources
Raw biogas electricity generation (biogas CHP)	Costs 2013	€/kW	560	[46]
	Costs 2050	€/kW	500	[46]
	K-exponent	-	1.7	Own assumptions
	Service life	a	20	[47, 48] expert survey
	M/O costs	% investment	2.5	Expert survey
	Calc. interest	%	7	Own assumptions
Bio natural gas upgrading	Costs 2013	€/kWh	750	[49]; expert survey
	Costs 2050	€/kWh	240	[49]; expert survey
	K-exponent	-	3	Own assumptions
	Service life	a	25	[50]
	M/O costs	% investment	3	[51]; expert survey
	Degree of efficiency	%	88	[51];[52]; [53]
	Calc. interest	%	7	[50]
Solid biomass to CH_4	Costs 2013	€/kW	2426	[54]; [55]
	Costs 2050	€/kW	1244	[54]; [55]
	K-exponent	-	3	Own assumptions
	Service life	a	20	[56]
	M/O costs	% investment	6	[51]
	Full load hours	H	8000	Based on [55]
	Degree of efficiency	%	61	[51]
	Calc. interest	%	7	Own assumptions

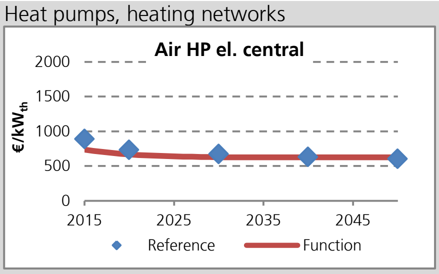
Component	Variable	Unit	Value	Sources
Solid biomass to H2	Costs 2013	€/kW	3670	[51]; [54]; [55]
	Costs 2050	€/kW	1882	[51];[54]; [55]
	K-exponent	-	3	Own assumptions
	Service life	a	20	[56]
	M/O costs	% investment	6	[51]
	Full load hours	h	8000	Corresponding solid biomass to CH4
	Degree of efficiency	%	48	[51]
	Calc. interest	%	7	Own assumptions
Solid biomass to fuel	Costs 2013	€/kW	3315	[54]; [55]
	Costs 2050	€/kW	1700	[54]; [55]; degression according to biomass gasification
	K-exponent	-	2	Own assumptions
	Service life	a	20	[56]
	M/O costs	% investment	6	[51]
	Full load hours	H	8000	[55]
	Degree of efficiency	%	46	[57], [56];[51]
	Calc. interest	%	7	Own assumptions
Solid biomass combustion, industry	Costs 2013	€/kW	468	[58]
	Costs 2050	€/kW	405	[58]; degression according to biomass boiler/wood boiler
	K-exponent	-	5	Own assumptions
	Service life	a	20	Assumption: same service life as other boilers
	M/O costs	% investment	3	Own assumptions
	Calc. interest	%	7	Own assumptions
Biodiesel plant (from rape bio cultivation)	Costs 2013	€/kW	150	[55]
	Costs 2050	€/kW	150	[55]
	K-exponent	-	1	Own assumptions
	Service life	a	20	[47]
	M/O costs	% investment	5	[51]
	Full load hours	h	5500	[55]
	Degree of efficiency	%	60	[59]
	Calc. interest	%	7	Own assumptions

Component	Variable	Unit	Value	Sources
Biogas plant	Costs 2013	€/kW	1105	[55];[49]; expert survey
	Costs 2050	€/kW	697	Expert survey
	K-exponent	-	3	Own assumptions
	Service life	a	20	[47]; expert survey
	M/O costs	% investment	5	[51]; expert survey
	Full load hours	h	8400	Expert survey
	El. WG.	%	25	[46]
	Th. WG.	%	40	[46]
	CO2 factor	0.12	t CO2-eq/MWh	[55]
	Calc. interest	%	7	Own assumptions

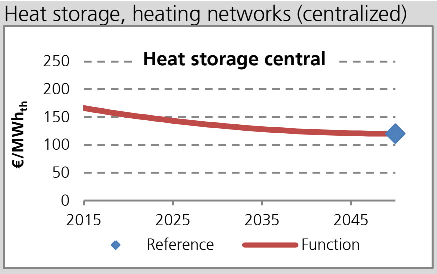


Heating networks

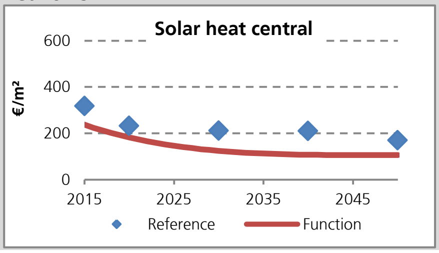
Component	Variable	Unit	Value	Sources
Heat pumps, heating networks	Costs 2013	€/kW	781	[60]; [61]
	Costs 2050	€/kW	625	[60]; [61]
	K-exponent	-	6	Own assumptions
	Service life	a	20	[43]
	M/O costs	% investment	3.5	Own assumptions
	Calc. interest	%	7	Own assumptions

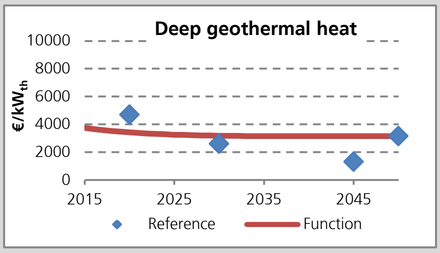
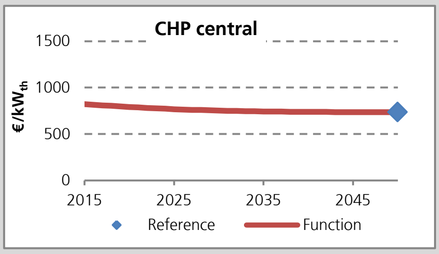


Component	Variable	Unit	Value	Sources
Heat storage, heating networks (centralized)	Costs 2013	€/m³	171	Own calculations based on [62]
	Costs 2050	€/m³	120	Own calculations based on [62]
	K-exponent	-	2	Own assumptions
	Service life	a	40	Own assumptions
	M/O costs	% investment	1	Own assumptions
	Calc. interest	%	7	Own assumptions

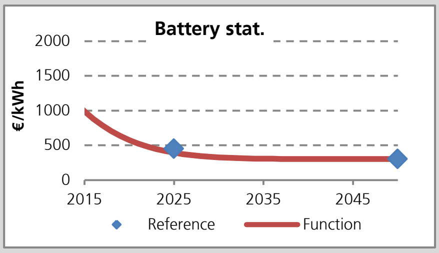
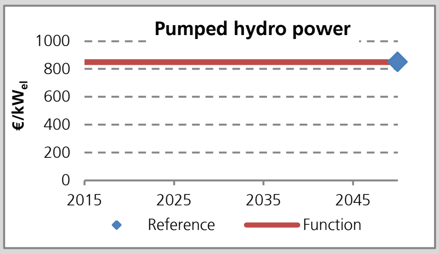


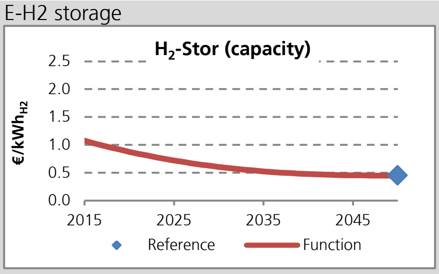
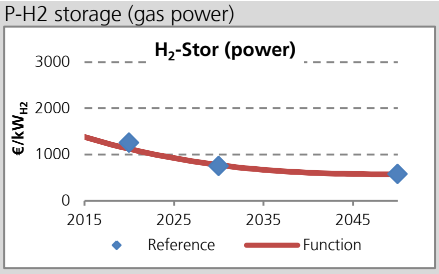
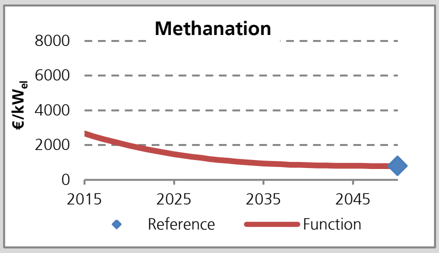
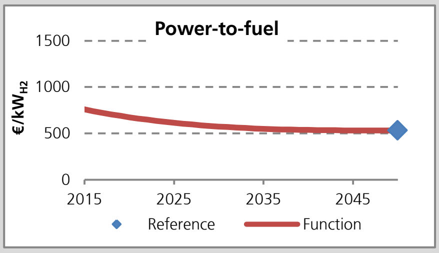
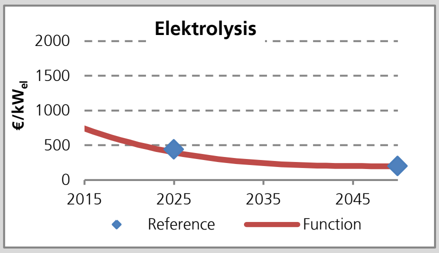
Component	Variable	Unit	Value	Sources
Solar thermal energy systems, heating networks	Costs 2013	€/m²	265	[40, 63]
	Costs 2050	€/m²	106	[40, 63]
	K-exponent	-	3.5	Own assumptions
	Service life	a	30	[64]
	M/O costs	% investment	1.4	[65]
	Calc. interest	%	7	Own assumptions

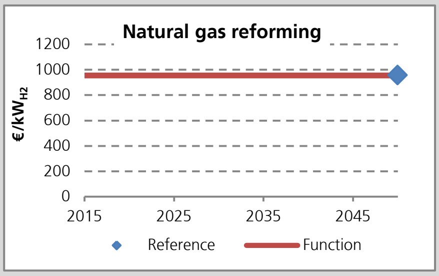


Component	Variable	Unit	Value	Sources
Deep geothermal energy, heating networks	Costs 2013	€/kW	3936	[66]); [67]; expert survey
	Costs 2050	€/kW	3146	[66]); [67]; expert survey [68–75][67], [68], [69], [70], [71], [72], [73], [74]
	K-exponent	-	5	[76]
	Service life	a	22	Expert survey
	M/O costs	% investment	3.65	Expert survey
	Calc. interest	%	7	Own assumptions
CHP, heating networks	Costs 2013	€/kW	839	[40], [77]; [46];[42], [78], [79]
	Costs 2050	€/kW	736	[40]; [77]; [46];[42]; [78]; [79]
	K-exponent	-	3	Own assumptions
	Service life	a	22	[42]
	M/O costs	% investment	3	Own assumptions
	Capacity	MW	125	Own assumptions
	Calc. interest	%	7	Own assumptions

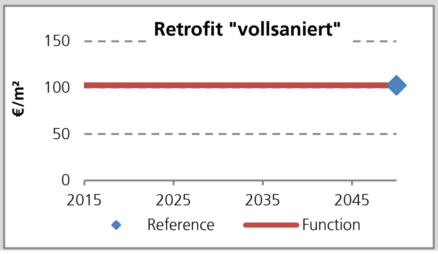
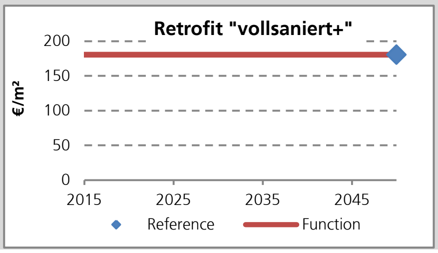
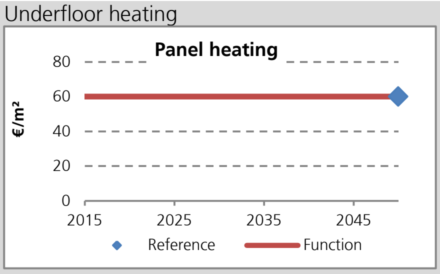
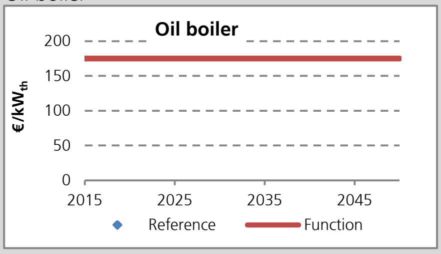
Storage technologies and others

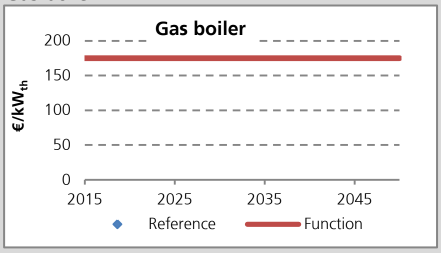
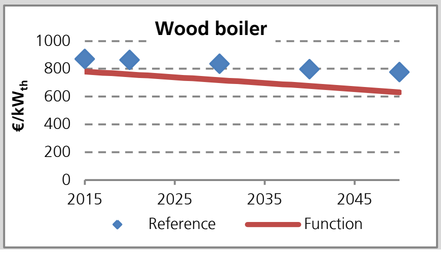
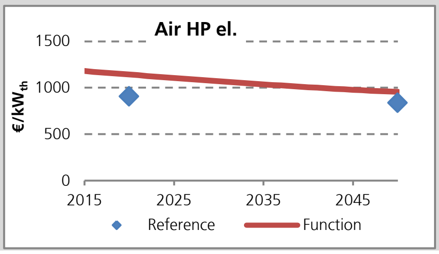
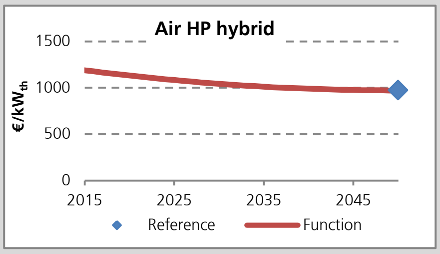
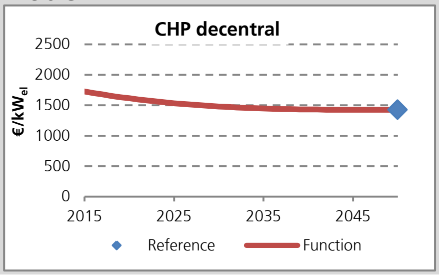
Component	Variable	Unit	Value	Sources
Stationary batteries	Costs 2013	€/kWh	1260	[80];[81]
	Costs 2050	€/kWh	304	[80]; expert survey
	K-exponent	-	6	Own assumptions
	Service life	a	25	[45]; expert survey
	M/O costs	% investment	1	Own assumptions
	Degree of efficiency	%	95	[45]
	Calc. interest	%	4	Own assumptions
Pumped storage plants	Yearly fixed storage power	8.6	GW	[19]
	Yearly fixed storage capacity	51.6	GWh	[19] [82]
	Costs 2013	850	€/kW	Assumption: no cost degression, thus value from [83, 84] expert survey
	Costs 2050	850	€/kW	Expert survey
	Costs, O&M	1	%/a	Expert survey
	Degree of efficiency	80%	%	[19]
	Service life	80	a	Expert survey

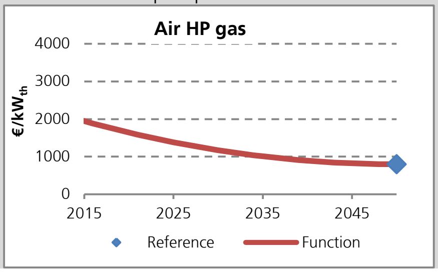
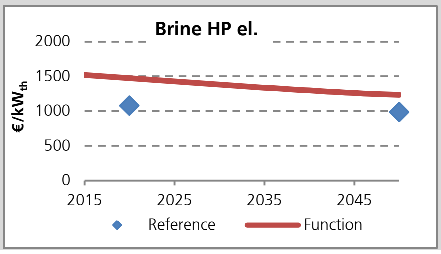
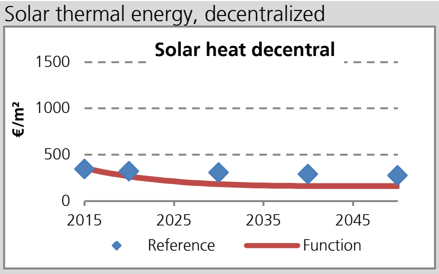
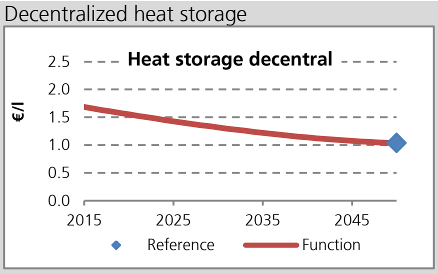
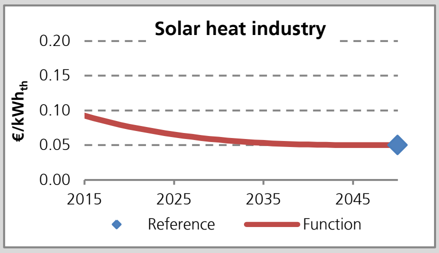
Component	Variable	Unit	Value	Sources
E-H2 storage	Costs 2013	€/kWh	1.17	Own assumptions
	Costs 2050	€/kWh	0.45	Own assumptions
	K-exponent	-	2.5	Own assumptions
	Service life	a	40	Expert survey
	M/O costs	% investment	1.6	Expert survey
	Calc. interest	%	7	Own assumptions
P-H2 storage (gas power)	Costs 2013	€/kW	1500	Cost degression from 2013 to 20150 acc. to E-H2 storage
	Costs 2050	€/kW	575	Expert survey
	K-exponent	-	2.5	Expert survey
	Service life	a	25	[80]
	M/O costs	% investment	1.6	Expert survey
	Calc. interest	%	7	Own assumptions
Sabatier	Costs 2013	€/kW	3000	Expert survey
	Costs 2050	€/kW	800	[85]; expert survey
	K-exponent	-	3	Own assumptions
	Service life	a	25	[85]; expert survey
	M/O costs	% investment	2.5	[85]; expert survey
	Sabatier degree of efficiency	%	80	[85]; expert survey
	Electrolysis degree of efficiency	%	80	[84]; expert survey
	Th. degree of efficiency	%	6.8	Own assumptions
	Calc. interest	%	7	Own assumptions
Power-to-fuel	Costs 2013	€/kW	800	Own calculations based on [86]
	Costs 2050	€/kW	532	Own calculations based on [86]
	K-exponent	-	3	Own assumptions
	Service life	a	30	[87]
	M/O costs	% investment	4	Own assumptions
	Degree of efficiency	%	66.5	[88]
	Calc. interest	%	7	Own assumptions
Electrolysis	Costs 2013	€/kW	840	Expert survey
	Costs 2050	€/kW	200	Expert survey
	K-exponent	-	3	Expert survey
	Service life	a	18.5	Expert survey
	M/O costs	% investment	4	Expert survey
	Degree of efficiency	%	80	[19]
	Calc. interest	%	7	Own assumptions

Component	Variable	Unit	Value	Sources
P-H2 reforming fossil	Costs 2013	€/kW	955	[89]; [90]
	Costs 2050	€/kW	955	[89]; [90]
	K-exponent	-	1	Own assumptions
	Service life	a	15	[91];[92] [89]
	M/O costs	% investment	2.5	[89]
	Degree of efficiency	%	80	[93]; [89]
	Calc. interest	%	7	Own assumptions

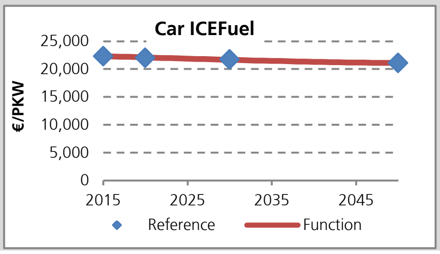
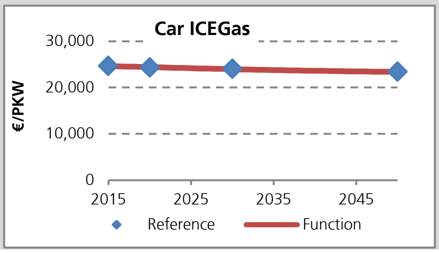
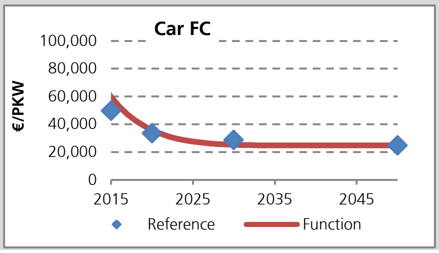
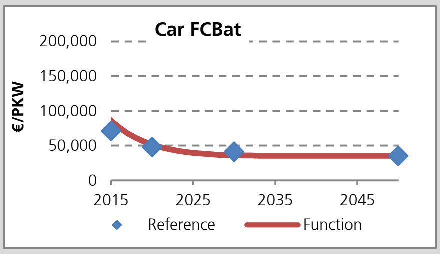
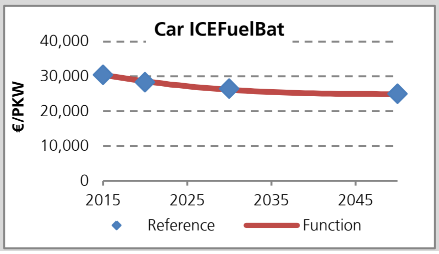
Building and heating technologies

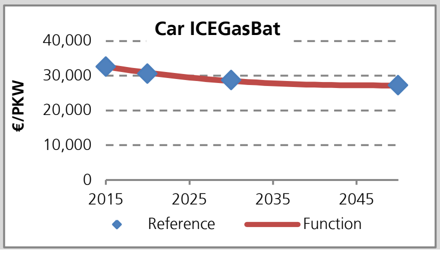
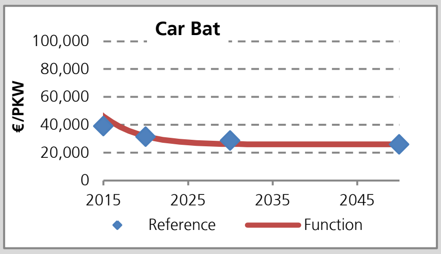
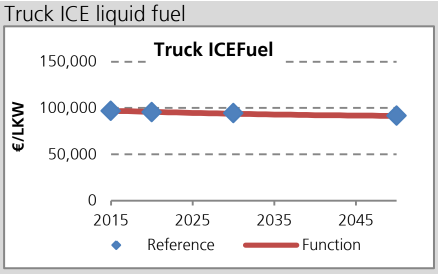
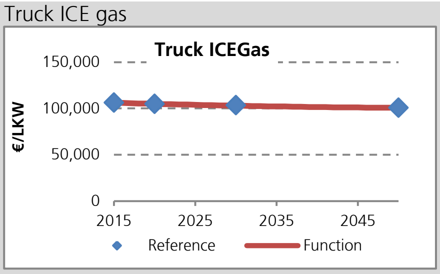
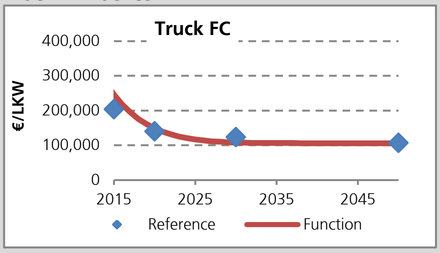
Component	Variable	Unit	Value	Sources
Building, fully renovated	Costs 2013	€/m²	102	[94]; [15]; [14]; [13]; [95]
	Costs 2050	€/m²	102	[94]; [15]; [14]; [13]; [95]
	K-exponent	-	1	Own assumptions
	Service life	a	50	Own assumptions
	M/O costs	% investment	1	Own assumptions
	Calc. interest	%	4	Own assumptions
Building, fully renovated plus	Costs 2013	€/m²	180	[94];[15];[14]; [13]; [95]
	Costs 2050	€/m²	180	[94];[15];[14]; [13]; [95]
	K-exponent	-	1	Own assumptions
	Service life	a	50	Own assumptions
	M/O costs	% investment	1	Own assumptions
	Calc. interest	%	4	Own assumptions
Underfloor heating	Costs 2013	€/kW	60	[96]
	Costs 2050	€/kW	60	[96]
	K-exponent	-	0	Own assumptions
	Service life	a	50	Own assumptions
	M/O costs	% investment	1.5	Own assumptions
	Calc. interest	%	4	Own assumptions
Oil boiler	Costs 2013	€/kW	175	[40]; [97]
	Costs 2050	€/kW	140	[40]; [97]
	K-exponent	-	1.1	[40]
	Service life	a	20	According to gas boiler
	M/O costs	% investment	2	[98]
	Calc. interest	%	4	Own assumptions

Component	Variable	Unit	Value	Sources
Gas boiler	Costs 2013	€/kW	175	[40]
	Costs 2050	€/kW	175	[40]
	K-exponent	-	1.1	[40]
	Service life	a	20	[99]
	M/O costs	% investment	2	[98]
	Calc. interest	%	4	Own assumptions
Biomass boiler/wood boiler	Costs 2013	€/kW	788	[100]; [40]; [65];[58]
	Costs 2050	€/kW	631	[100]; [40]; [65];[58]
	K-exponent	-	0.95	[40]
	Service life	a	20	According to gas boiler
	M/O costs	% investment	3	Own assumptions
	Calc. interest	%	4	Own assumptions
Electrical heat pump, outside air	Costs 2013	€/kW	1195	[61];[101]; [102]; [103]
	Costs 2050	€/kW	956	[61];[101]; [102]; [103]
	K-exponent	-	1.2	[104]
	Service life	a	20	[43]
	M/O costs	% investment	3.5	Own assumptions
	Calc. interest	%	4	Own assumptions
El/gas hybrid heat pump air	Costs 2013	€/kW	1215	Assumption: (Costs heat pump-air+costs gas-BWK)*0.9
	Costs 2050	€/kW	972	Assumption: Costs 2013*0.8 (WP degression acc. to [61]
	K-exponent	-	2	Own assumptions
	Service life	a	20	[43]
	M/O costs	% investment	3	Own assumptions
	Calc. interest	%	4	Own assumptions
Micro CHP	Costs 2013	€/kW	1780	[42, 46]
	Costs 2050	€/kW	1424	[42, 46]
	K-exponent	-	3	Own assumptions
	Service life	a	20	[42]
	M/O costs	% investment	3	Own assumptions
	Calc. interest	%	4	Own assumptions

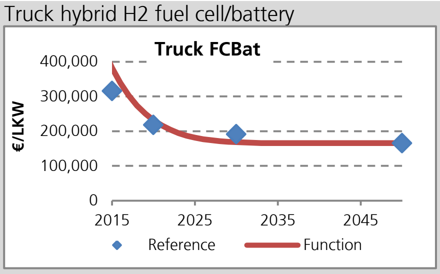
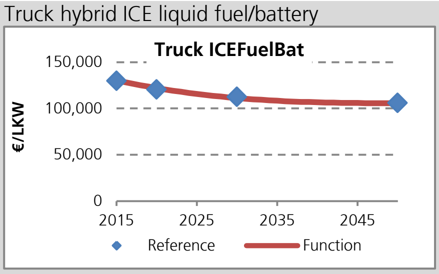
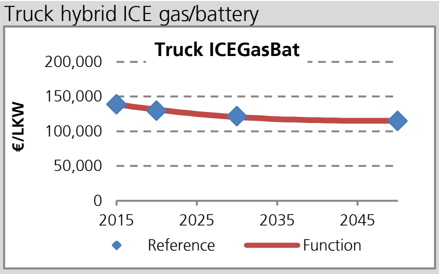
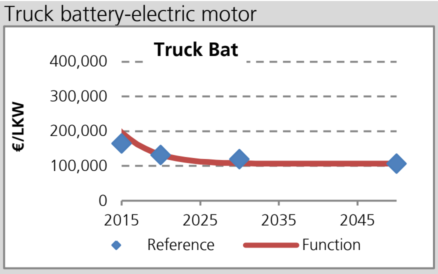
Component	Variable	Unit	Value	Sources
Gas-driven heat pump	Costs 2013	€/kW	2081	[60]; [105]
	Costs 2050	€/kW	800	[60]; [105]
	K-exponent	-	2	Own assumptions
	Service life	a	20	[43]
	M/O costs	% investment	1.5	Own assumptions
	Calc. interest	%	4	Own assumptions
Electrical heat pump, ground	Costs 2013	€/kW	1540	[61]; [101];[102]; [103]
	Costs 2050	€/kW	1232	[61]; [101];[102]; [103]
	K-exponent	-	1.2	[104]
	Service life	a	20	[43]
	M/O costs	% investment	3.5	Own assumptions
	Calc. interest	%	4	Own assumptions
Solar thermal energy, decentralized	Costs 2013	€/m²	405	[106];[40]
	Costs 2050	€/m²	162	[106]); [40]
	K-exponent	-	4	[106]); [40]
	Service life	a	30	[64]
	M/O costs	% investment	1.3	[65]
	Calc. interest	%	4	Own assumptions
Decentralized heat storage	Costs 2013	€/l	1.74	[98];
	Costs 2050	€/l	1.04	[98];
	K-exponent	-	2	Own assumptions
	Service life	a	20	[99]
	M/O costs	% investment	1.3	Own assumptions
	Calc. interest	%	4	Own assumptions
Solar thermal energy, industrial process	Costs 2013	€/kWh	0.1	[107]
	Costs 2050	€/kWh	0.05	[108]; [76]; [108] calculates with a heat price of slightly over 50 €/MWh for specific projects; in [76], a reduction of the heat price from solar thermal energy of 8 - 25 ct/kWh to 4 - 9 ct/kWh is expected until 2050 (drinking water pipeline (hot) and space heating, no prices specified for industry)
	K-exponent	-	3	Own assumptions
	Service life	a	30	[64]
	M/O costs	% investment	1.3	[65]
	Calc. interest	%	7	Own assumptions

Mobility

Component	Variable	Unit	Value	Sources
Passenger cars ICE liquid fuel	Costs 2013	€/car	22429	[109]
	Costs 2050	€/car	21100	[109]
	K-exponent	-	1.4	Own assumptions
	Service life	a	15	[109]
	M/O costs	% investment	1.6	[109]
	Calc. interest	%	7	Own assumptions
Passenger cars ICE gas	Costs 2013	€/car	24729	[109]
	Costs 2050	€/car	23400	[109]
	K-exponent	-	1.4	Own assumptions
	Service life	a	15	[109]
	M/O costs	% investment	1.4	[109]
	Calc. interest	%	7	Own assumptions
Passenger cars H2 fuel cell	Costs 2013	€/car	77600	[109]
	Costs 2050	€/car	24800	[109]
	K-exponent	-	7.5	Own assumptions
	Service life	a	15	[109]
	M/O costs	% investment	0.9	[109]
	Calc. interest	%	7	Own assumptions
Passenger car hybrid H2 fuel cell/battery	Costs 2013	€/car	110857	Own assumptions
	Costs 2050	€/car	35429	Own assumptions
	K-exponent	-	7.4	Own assumptions
	Service life	a	15	Assumption: Same as other drive concepts
	M/O costs	% investment	1	Own assumptions
	Calc. interest	%	7	Own assumptions
Passenger car hybrid ICE liquid fuel/battery	Costs 2013	€/car	31275	[109]
	Costs 2050	€/car	24900	[109]
	K-exponent	-	2.65	Own assumptions
	Service life	a	15	[109]
	M/O costs	% investment	1.3	[109]
	Calc. interest	%	7	Own assumptions

Component	Variable	Unit	Value	Sources
Passenger car hybrid ICE gas/battery	Costs 2013	€/car	33463	[109]
	Costs 2050	€/car	27200	[109]
	K-exponent	-	2.57	Own assumptions
	Service life	a	15	[109]
	M/O costs	% investment	1.3	[109]
	Calc. interest	%	7	Own assumptions
Passenger car battery-electric motor	Costs 2013	€/car	57450	[109]
	Costs 2050	€/car	26000	[109]
	K-exponent	-	8.09	Own assumptions
	Service life	a	15	[109]
	M/O costs	% investment	0.9	[109]
	Degree of efficiency	%	68	[109]
	Calc. interest	%	7	Own assumptions
Truck ICE liquid fuel	Costs 2013	€/truck	97502	Own assumptions and calculations
	Costs 2050	€/truck	91605	Own assumptions and calculations*
	K-exponent	-	1.6	Own assumptions
	Service life	a	15	Assumption: Same as passenger car [109]
	M/O costs	% investment	1.6	Assumption: Same as passenger car [109]
	Calc. interest	%	7	Own assumptions
Truck ICE gas	Costs 2013	€/truck	106681	Own assumptions and calculations*
	Costs 2050	€/truck	100783	Own assumptions and calculations*
	K-exponent	-	1.6	Own assumptions
	Service life	a	15	Assumption: Same as passenger car [109]
	M/O costs	% investment	1.4	Assumption: Same as passenger car [109]
	Calc. interest	%	7	Own assumptions
Truck H2 fuel cell	Costs 2013	€/truck	319925	Own assumptions and calculations*
	Costs 2050	€/truck	106310	Own assumptions and calculations*
	K-exponent	-	7.7	Own assumptions
	Service life	a	15	Assumption: Same as passenger car [109]
	M/O costs	% investment	0.9	Assumption: Same as passenger car [109]
	Calc. interest	%	7	Own assumptions

* Based on the costs for truck ICE liquid fuel, the costs of other drive concepts were calculated acc. to the cost differences for passenger cars.

Component	Variable	Unit	Value	Sources
Truck hybrid H2 fuel cell/battery 	Costs 2013	€/truck	497430	Own assumptions and calculations*
	Costs 2050	€/truck	165294	Own assumptions and calculations*
	K-exponent	-	7.7	Own assumptions
	Service life	a	15	Assumption: Same as passenger car
	M/O costs	% investment	1	Own assumptions
	Calc. interest	%	7	Own assumptions
Truck hybrid ICE liquid fuel/battery 	Costs 2013	€/truck	134022	Own assumptions and calculations*
	Costs 2050	€/truck	105722	Own assumptions and calculations*
	K-exponent	-	2.65	Own assumptions
	Service life	a	15	Assumption: Same as passenger car [109]
	M/O costs	% investment	1.3	Assumption: Same as passenger car [109]
	Calc. interest	%	7	Own assumptions
Truck hybrid ICE gas/battery 	Costs 2013	€/truck	142702	Own assumptions and calculations*
	Costs 2050	€/truck	114901	Own assumptions and calculations*
	K-exponent	-	2.6	Own assumptions
	Service life	a	15	Assumption: Same as passenger car [109]
	M/O costs	% investment	1.3	Assumption: Same as passenger car [109]
	Calc. interest	%	7	Own assumptions
Truck battery-electric motor 	Costs 2013	€/truck	246437	Own assumptions and calculations*
	Costs 2050	€/truck	106822	Own assumptions and calculations*
	K-exponent	-	8.08	Own assumptions
	Service life	a	15	Assumption: Same as passenger car [109]
	M/O costs	% investment	0.9	Assumption: Same as passenger car [109]
	Calc. interest	%	7	Own assumptions

* Based on the costs for truck ICE liquid fuel, the costs of other drive concepts were calculated acc. to the cost differences for passenger cars

Appendix 2: Expansion limits for technologies used

Table 4: Guidelines for maximum possible technology expansion

Component	Expansion	Unit	2015	2020	2030	2040	2050	2015-2050	Sources
Wind Offshore	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.6	1.1	1.2	1.2	1.2	45	Expansion per year: own assumption; max. expansion acc. to [19]
Wind Onshore	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	3.80	4.00	4.00	4.00	4.00	189	Expansion per year: own assumption; max. expansion acc. to [19]
Photovoltaics	Min.	GW	0	0	0	0	0	0.0	
	Max.	GW	3.40	5.00	5.00	5.00	5.00	275 +25	Expansion per year: own assumption; max. expansion acc. to [19]
Raw biogas electricity generation (el. power)	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	1	1	1	1	1	36.0	Own assumptions
Combined cycle power plant	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	1	1	1	1	1	36.0	Own assumptions
Gas turbine	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	4	4	4	4	4	144.0	Own assumptions
Power-to-fuel	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	1	1	1	1	1	36.0	Own assumptions
Sabatier	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.20	0.70	1.70	6	7	126.9	Own assumptions
P-H2 storage (gas power)	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0	1	3	6	7	131.4	Own assumptions
P-H2 reforming fossil	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.1	0.4	0.9	1	1	27.5	Own assumptions
Electrolysis	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.20	0.70	2.75	6	7	131.4	Own assumptions
Stationary batteries	Min.	GWh	0	0	0	0	0	0.0	Own assumptions
	Max.	GWh	1.2	2.2	4.2	5	5	142.6	Own assumptions
E-H2 storage	Min.	GWh	0	0	0	0	0	0.0	Own assumptions
	Max.	GWh	200	500	1000	2000	5000	60900.0	Expansion per year: own assumption; max. expansion acc. to [19], [110]
Bio natural gas upgrading	Min.	TWh	0.00	0.00	0.00	0	0	0.0	Own assumptions
	Max.	TWh	0.20	0.45	0.95	1	1	29.2	Expansion per year: own assumption; max. expansion acc. to biomass potential acc. to

Component	Expansion	Unit	2015	2020	2030	2040	2050	2015-2050	Sources
Biomass gasification to CH_4	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.1	0.2	1	1	1	27.9	Own assumptions
Biomass gasification to H_2	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.1	0.2	1	1	1	27.9	Own assumptions
Biomass gasification to fuel	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.1	0.2	1	1	1	27.9	Own assumptions
Solid biomass combustion, industry	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.1	0.2	2	2	2	48.9	Own assumptions
Biodiesel	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.55	0.80	1	1	1	33.8	Own assumptions
Biogas plant	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	1	1	1	1	1	36.0	Own assumptions
Deep geothermal energy, heating networks	Min.	GW	0.005	0.005	0.005	0.005	0.005	0.2	Own assumptions
	Max.	GW	0.005	0.005	0.005	0.005	0.005	0.2	Own assumptions
CHP, heating networks	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	1	1	1	1	1	18.0	Own assumptions
Solar thermal energy, decentralized	Min.	kW_{ST}/kW_{HT}[1]	0	0	0	0	0	0.0	Own assumptions
	Max.	kW_{ST}/kW_{HT}			2			-	Own assumptions
Decentralized heat storage	Min.	Million l	0.1	0.1	0.1	0.1	0.1	3.6	Own assumptions
	Max.	Million l	10	10	10	10	10	360.0	Own assumptions
Heat pumps, heating networks	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.2	0.5	0.5	0.5	1	17.4	Own assumptions
Heat storage, heating networks	Min.	GWh	0	0	0	0	0	0.0	Own assumptions
	Max.	GWh	2	7	50	50	50	1344.0	Own assumptions
Solar thermal energy systems, heating networks	Min.	GW	0	0	0	0	0	0.0	Own assumptions
	Max.	GW	0.3	0.8	2	2	2	59.2	Own assumptions, max. expansion acc. to solar energy potential limit [19]
Solar thermal energy industry process (percentage of total thermal load in industry)	Min.	-	0	0	0	0	0	0	Own assumptions
	Max.	-	0.01	0.01	0.01	0.01	0.01	0.05	Own assumptions

[1] Solar thermal energy power (ST) per installed heating technology power (HT)

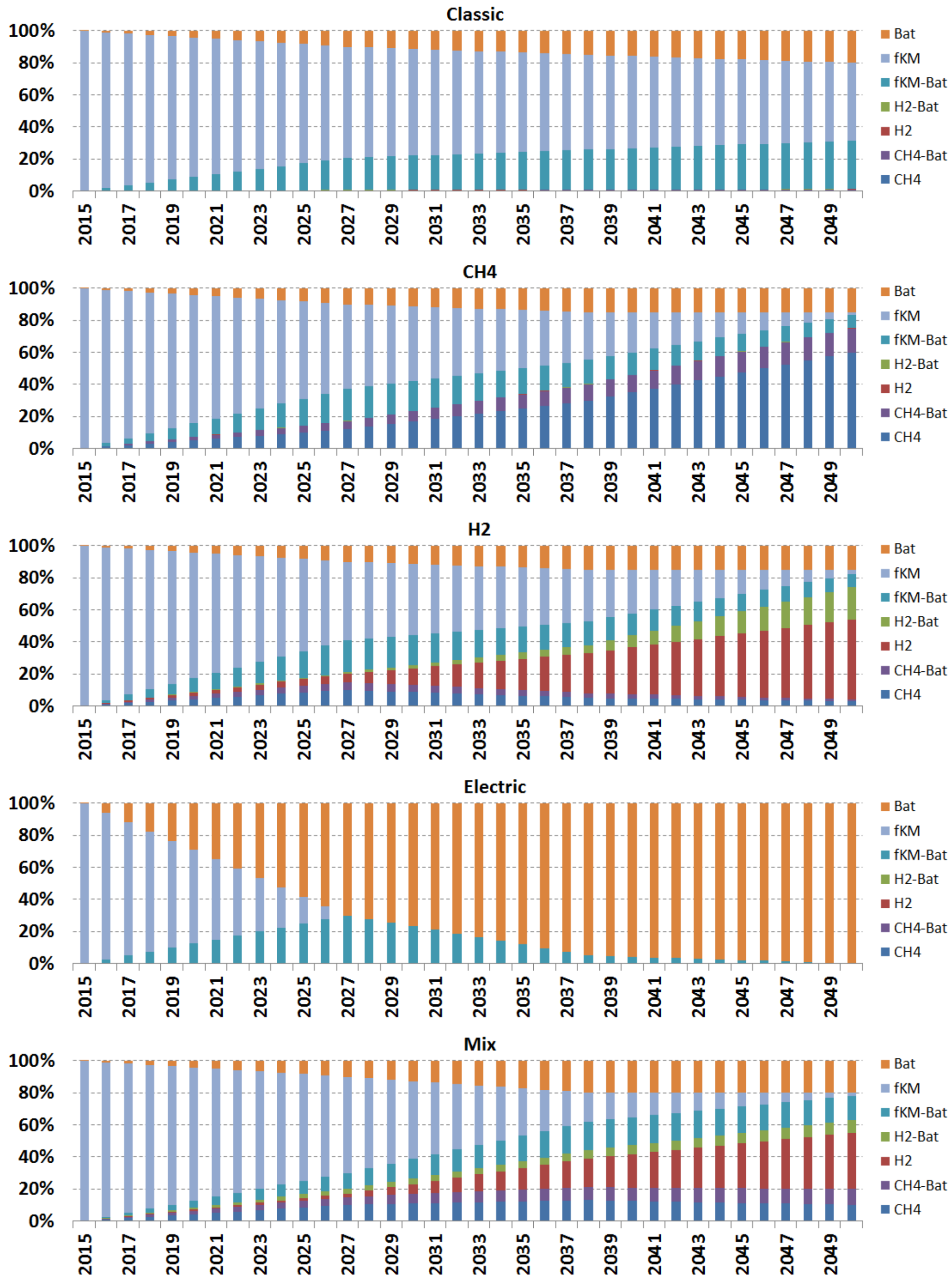
Appendix 3: Development of conventional power plants

Table 5: Development of conventional power plants until 2050

Component	Variable	Unit	2015	2020	2030	2040	2050	Sources
Nuclear power plants	inst. capacity	GW	12.1	8.1	0	0	0	[24]
Coal-fired plants	inst. capacity	GW	29.5	25.9	17.5	8.1	7.6	[24]
Lignite plants	inst. capacity	GW	20.2	16.37	10.9	8.9	2.9	[24]
Oil-fired power plant	inst. capacity	GW	2.3	1.3	0.8	0.3	0.1	[24]
Combined cycle power plant	inst. capacity	GW	14.7	14.7	14.1	11.0	5.1	[24]
Hydropower plants	inst. capacity	GW	5.3	5.3	5.3	5.3	5.3	[24]
Pumped storage plants	inst. capacity	GW	6.7	7.0	7.0	7.0	7.0	[24]

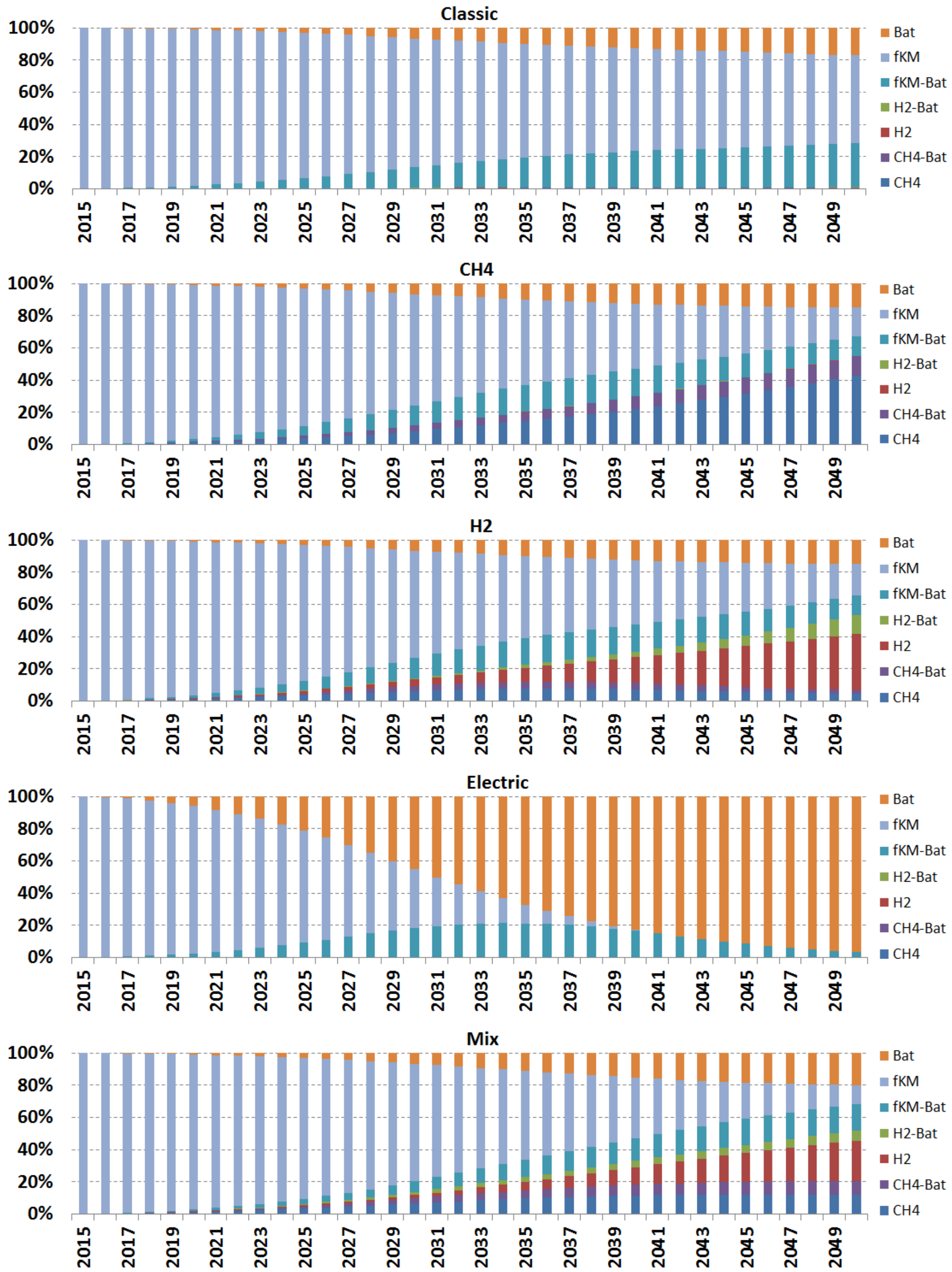
Appendix 4: Vehicle development mobility scenarios

The following figure shows the market development for vehicle concepts for motorised private transport in the five investigated scenarios. The chart shows the respective portion of each drive concept in the vehicles sold in the respective year.



Legend:
Bat: Vehicles with battery/electric motor
fKM: Vehicles with combustion engine with liquid fuel mix
H2: Vehicles with hydrogen fuel cell and electric motor
CH4: Vehicles with combustion engine and gaseous fuel
fKM-Bat, H2-Bat, CH4-Bat: Hybrid concepts with battery/electric motor

The following figure shows the vehicle fleet development for vehicle concepts for motorised private transport in the five investigated scenarios. The chart shows the respective portion of each drive concept in the vehicle fleet in the respective year taking into account the mean vehicle turnover rate.



Legend:
Bat: Vehicles with battery/electric motor
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fKM-Bat, H2-Bat, CH4-Bat: Hybrid concepts with battery/electric motor

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