Renewables versus fossil fuels – comparing the costs of electricity systems

Electricity system designs for 2050 – An analysis of renewable and conventional power systems in Germany

ANALYSIS

Agora Energiewende

Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

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IMPRINT

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Preface

Dear readers,

the year 2050 is associated with many hopes and fears. By this year, Germany aims to complete its transition to a power system based almost completely on renewables. But will such a system be financially feasible?

To answer this question, we asked experts at the Öko-Institut to study various options for the future design of the power system, and to compare their costs.

The study considers four different scenarios for the power system in 2050: two scenarios based on fossil fuels (one on coal, and one on natural gas), and two scenarios for renewables-based systems that differ in their deployment of storage technology. In this "2x2" comparison, the authors assess the total system costs and CO_2 emissions produced by alternative configurations of the power system.

A key finding of the study is that the relative advantages associated with each scenario heavily depend on future fuel and CO_2 prices. And while it is difficult to estimate the prices that will prevail in 2050, the thought experiment conducted in this study does make one thing clear: abandoning the energy transition does not mean that energy costs vanish – it just leads to different costs. And these might just turn out to be higher than expected.

I hope you enjoy reading this insightful study.

Best regards,
Patrick Graichen
Director of Agora Energiewende

Key findings at a glance:

1 **A power system with a 95 percent share of renewables has the same or even lower costs than a fossil-based system under most assumptions for future fuel and CO_2 prices.** A coal-based system would only be significantly less expensive if extremely low CO_2 prices are expected in 2050 (20 euros/t). Similarly, a natural gas-based system would only be significantly less expensive if gas prices are low and CO_2 prices are not high (i.e. below 100 euros/t).

2 **A renewables-based system insulates the economy against volatile commodity prices, as the costs of fossil-based systems heavily depend on fuel and CO_2 price trends.** Variable costs (largely for fuel and CO_2) account for 30 to 67 percent of the total costs of the fossil-based systems. By contrast, variable costs represent just 5 percent of costs in the renewables-based systems.

3 **A power system with a 95 percent share of renewables reduces CO_2 emissions by 96 percent their 1990 levels at CO_2 abatement costs of about 50 euros/t.** A renewables based energy transition can thus be considered efficient climate policy, as CO_2 damage costs are estimated a lot higher (80 euros/t over the short-term, and at 145 to 260 euros/t over the long term).

Summary

The decarbonization of energy systems is a crucial component of any serious climate protection strategy. For the electricity sector, this ultimately means the transition from a power system based on coal and natural gas to one almost completely based on renewable energy by 2050.

The technical feasibility of an electricity system with a greater than 90 percent share of renewables is no longer disputable today. Such a system is possible thanks to recent technological advances, particularly in the area of wind and solar energy, as well as foreseeable developments in harnessing flexibility (including flexible demand, battery storage and power-to-gas technologies).

However, questions surrounding the costs of this new electricity system have not yet been satisfactorily answered. One problem is that cost estimates need to take into account the total costs of an electricity system based on renewables and compare it to a system based on fossil fuels. Against this backdrop, this study seeks to answer the following questions:

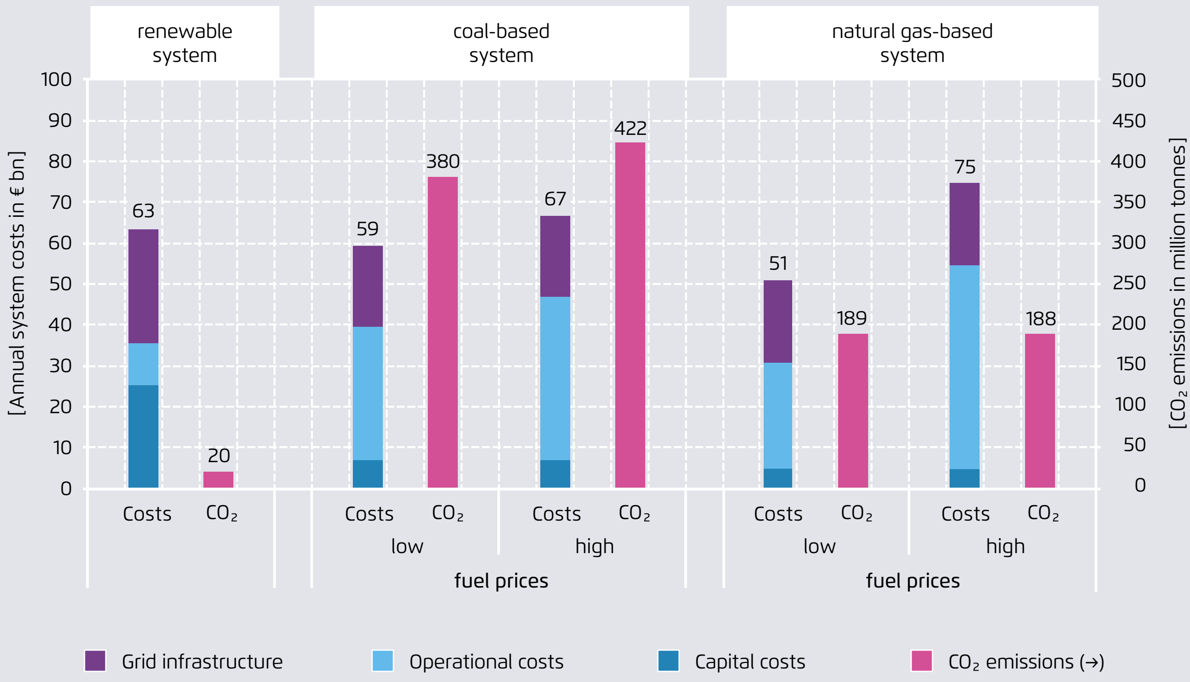
→ What are the technical features and cost structures of a power system when over 90 percent of electricity is generated from renewables in 2050? How do the costs of different storage strategies (batteries vs. power-to-gas) compare?
→ What technical features, cost structures and emissions figures result for a hypothetical fossil-based power system in 2050 if we immediately cease construction of additional wind and solar power? How do the costs of different fossil-based power systems compare (i. e. a conventional mix of lignite/hard coal/natural gas power plants vs. a power system based purely on natural gas)?

To answer these questions, a number of model calculations were carried out for Germany using different framework conditions. Sensitivity analyses were performed to verify the robustness of the results. The following conclusions can be drawn from our calculations:

1. There are various options for the development of an electricity system based on renewables up to 2050. These options differ with a view to the composition of the renewable energy mix and the interactions between grid infrastructure and flexibility options. Analysis using hourly resolutions shows that a renewable energy fleet could cover Germany's power supply in full while also ensuring security of supply.
2. If the cost of a tonne of carbon dioxide (CO_2) is 50 euros or more in 2050, a renewable energy power system would in most cases be less expensive than or comparable in cost to a conventional lignite/hard coal/natural gas-based power system (Figure S-1). This finding remains largely true regardless of the underlying fuel prices. Only when low CO_2 prices or a combination of low energy prices and CO_2 prices of less than 50 euros are assumed for 2050 does a lignite/hard coal/natural gas-based power mix lead to lower overall costs than a system based on renewables.
3. An electricity system based completely on natural gas power plants leads to similar or higher costs when high fuel prices are assumed. When low fuel prices are assumed, such a system is cheaper than a system based on renewables. This finding remains largely true regardless of CO_2 prices.
4. CO_2 emissions in relation to 1990 would be 7 percent to 24.5 percent lower with a new lignite/hard coal/natural gas-based electricity system, 59 percent lower with an electricity system based entirely on natural gas, and 96 percent lower with an electricity system based almost completely on renewables. In the final analysis, only a renewables-based system is compatible with the climate protection targets set forth by the Paris Agreement.
5. The CO_2 abatement costs associated with transitioning from a fossil-based system to one based

Comparison of total system costs of predominantly renewable, coal and natural gas-based power systems with CO_2 prices of €50, 2050

Figure S-1



Öko-Institut

almost fully on renewable energy are 40 to 60 euros per tonne of CO_2 in most scenarios. There are two exceptions: For the change from a power system based on natural gas to one based on renewable energy, emission reduction costs of approx. 125 euros per tonne of CO_2 arise when permanently low fuel prices are assumed. In the case of high fuel costs, however, negative emission reduction costs of –15 euros per tonne of CO_2 result.

In summary, a power system based largely on renewables in 2050 is not just technically feasible and necessary to meet climate protection targets – it is also attractive in terms of overall costs. In the most probable future scenarios for Germany, an electricity system based on renewables would be less or equally as expensive as a fossil-based power system.

Considering uncertainties in global commodity markets, a renewables-based system would have the additional advantage of shielding the national economy as a whole from volatile price fluctuations. This, in turn, would undergird the competitiveness of the German economy.

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1. Introduction

Preventing anthropogenic climate change is a grave challenge that will require the transformation of energy systems and the large-scale deployment renewable energy in coming years. Over the past two decades, tremendous improvements have been made in the technical capabilities and price competitiveness of electricity generation options based on renewables. However, there are still a number of open questions regarding the features of a renewable-based system, particularly with regard to flexibility options and grid infrastructure. Also, new challenges have arisen due to recent volatility in commodities markets, which makes it difficult to project and compare the costs of systems based on conventional fuels versus renewables.

In light of the need to fundamentally restructure the electricity system in Germany to one based on renewable energy, the questions involved can no longer be answered with sufficient reliability if different elements of the various systems (production plants, flexibility options, grid infrastructure) are analysed in isolation.

This study thus aims to conduct an integrated analysis of the elements impacting the various design options for a renewables-based system. In order to enable classification of the results, the analyses were conducted as a model-based thought experiment geared to answering the following five questions:

1. What are the different electricity system designs possible when over 90 percent of electricity supply is generated from renewable energy in 2050?
2. What would an electricity system look like in 2050 if no new wind and solar power plants were built in the future and if a fossil-based power system was retained?
3. How would these two power systems differ in terms of system costs and CO_2 emissions?
4. How robust are the results of such a comparison with respect to different developments in fuel, CO_2 and power plant costs as well as in terms of the different designs of renewable and fossil-based electricity systems?
5. What conclusions can be drawn from this?

Section 2 describes the methodological approach that was used to answer these questions. In section 3, the most important framework assumptions for the empirical analyses are shown, which for reasons of consistency are largely based on prior analyses conducted by Agora Energiewende. The results are concisely presented in section 4, which also includes the sensitivity analyses for classifying the assumptions made in section 3. The most important conclusions drawn from the analyses are provided in section 5.

2. Methodological approach

2.1. Basic approach

The first aim of this study is to determine and compare the overall costs of alternative power systems. These costs include:

- all costs for investment, fuel, raw materials, consumables, emission allowances, personnel, maintenance and repairs; and
- all elements of the power supply system, i. e. generation, grids and storage.

All costs are calculated on an annual basis. Capital costs for investments are converted to annual costs using the annuity method.

The CO_2 emissions produced by each alternative design for the power system are also determined in this study. These emissions are calculated based on power plant dispatch, as determined using a dispatch model, and are accounted for at the plant level. As a result, our emissions estimates include all emissions released by electricity generation plants. The emission levels are not adjusted to take into account the heat generated in combined heat and power plants.

The study considers alternative designs for the power system, taking into account different framework conditions for 2050. The calculation methods for investment costs take into account the growth dynamics of different system elements as well as relevant investment costs trends. For all other cost elements, the annual levels in 2050 are used in the calculations.

The thought experiment conducted within the scope of this analysis contains six steps:

1. In a first step, two designs for an electricity system that is largely based on renewable generation are developed (with renewable energy covering 95 percent of electricity demand).
   - For the power generation capacities of onshore and offshore wind power plants and photovoltaic systems (PV), identical expansion paths are assumed for both system designs, which are geared to the minimization of residual load.
   - We also calculate two different designs for the flexibility options needed to complement renewable power generation. In the first design, there is substantial use of battery storage. In the second design, the storage-side flexibility is provided exclusively by power-to-gas plants.

2. In a second step, two power system designs are elaborated, both of which assume that the expansion of wind and solar power plants is discontinued over the next few years and that by 2050 a fossil-based power system develops along the conventional structures of the past. Nuclear energy is excluded as a possible component of this electricity system.
   - In the first design, the system develops on the basis of the full costs for the different power generation options, as dictated by the conventional structure of base, medium and peak load generation. Climate policy restrictions play only an incidental role. Methodologically, this design is based on a simplified full cost model for fossil fuel power plants and historical load profiles.
   - In the second design, the system remains based on fossil fuels, but comes to rely on the least CO_2-intensive fossil fuel, i. e. natural gas. Methodologically, the development of the power plant fleet is based on the first design, but hard coal and lignite-fired power plants have been substituted with natural gas combined-cycle power plants (CCPs).

3. In a third step, we calculate dispatch for the generation system using an optimum cost approach for every hour of the year:
   - Based on the installed power generation capacities for renewable energy, the corresponding feed-in

profiles and the hourly electricity demand, a residual load curve is calculated.
- → For this residual load, the power plants and the flexibility options are dispatched according to their short-term marginal costs (i. e. essentially the costs for fuel and emission allowances and the efficiencies of storage) while taking into account diverse system restrictions. We also calculate electricity generation, short-term operating costs and CO_2 emissions.

4. In a fourth step, remaining cost components for the power systems are determined:
- → The capital costs for power plants and flexibility options are calculated on an annuity basis.
- → The fixed operating costs of the power plants and flexibility options are calculated by drawing on typical values.
- → The variable operating costs of the overall system are incorporated as a result derived from the dispatch model.
- → Supplementary calculations are made to determine additional operating costs associated with the fixed costs for the open-cast lignite mines and for the CO_2 needed for power-to-gas plants.
- → Supplementary calculations are also made to determine the costs of grid infrastructure.

5. In a fifth step, a number of indicators are determined to make classification of the results easier:
- → the power generation mix;
- → the CO_2 emissions of power generation;
- → the volume of surplus electricity from power generation plants based on renewable energy;
- → the surplus electricity from renewable energy power plants that is not transferred to short-term storage;
- → the use of surplus renewable electricity in combined cycle plants; the annual average utilization of these plants; the CO_2 demand for the production of synthetic methane (where applicable); and the electricity generation from plants that use gas produced from electricity, including their annual average utilization.

6. As the starting values are in some cases projected far into the future, we also conducted sensitivity analyses of key assumptions relevant to our input parameters.

The methodological approach described in the foregoing aims first and foremost to provide a robust assessment of the system costs associated with different future developments.

2.2. Definition of system boundaries

The electricity systems compared in this analysis constitute very different development paths for Germany's overall energy system. While a power system based predominantly on renewable energy is consistent with a development path in which the total energy system is decarbonized, a predominantly fossil fuel-based power system is only viable if only low or unambitious GHG emission reductions are to be achieved by 2050.

With a view to the decarbonization of the overall energy system, additional electricity demand may arise in the heating and transportation sectors, which could necessitate a significantly expanded power system (Fraunhofer IWES 2015, Oeko-Institut & Fraunhofer ISI 2015, 2015, UBA 2014b, Quaschning 2016). The magnitude of additional electricity demand depends on the scope of GHG emission reductions, the availability of sustainable biomass and synthetic-fuel production levels in other countries. The total calculated electricity demand has a substantial range, stretching from 450 to 800 – and in some versions to significantly above 1,000 – terawatt hours.

Since the importance of electricity as a form of energy can differ widely in the two overarching trajectories of the energy system and in the different decarbonization paths, the consistent definition of system boundaries is of central importance, above all for a reliable comparison of system costs. Two different approaches can be pursued in principle:

- The modelled power systems can be analysed assuming different levels of electricity demand. However, the costs for technologies that use electricity and the costs saved in the heating and transportation sectors of the energy system must be considered in their entirety (including investment, operating and infrastructure costs). The modelling carried out for this purpose cannot be restricted to the electricity sector; the whole energy system has to be parameterised and analysed. Forecasting up to 2050 requires substantial ranges to be considered, which can be modelled in principle using sensitivity calculations, but which would entail a huge increase in the overall number of calculations due to the combinatorics. One advantage of this approach, however, is that it allows a comprehensive cost assessment.
- A second possible approach is to compare power systems while assuming the same level of electricity demand. In connection with the decarbonization of the energy system, however, this approach might underestimate the absolute cost of the power system. However, it avoids extensive additional model and scenario calculations as well as the uncertainties that arise with the parameterisation of different developments in the heating and transportation sectors. While this has the disadvantage of excluding the cost differences associated with electricity systems of varying sizes, it enables the calculation of significantly more robust cost relationships.

Pragmatic considerations related to the structure of our thought experiment and available resources led to the selection of the second approach. Our analysis is thus primarily geared toward assessment of the cost ratios of different power system designs.

In addition, a number of simplifications were made to reduce the complexity of the calculations and to make fundamental interdependencies clearer:

- The study examines how domestic power demand is met with domestic generation and domestic flexibility options. Electricity imports and exports are not considered. As a result, the calculated system costs represent conservative estimates, especially when the modelled system has high flexibility needs, i. e. when there is a high share of renewable energy.
- Feedback effects from different framework conditions, the structure of the power generation fleet and variation in flexibility options were not included in the model calculations.
- The quantities of overproduction from renewable power plants used in other sectors were not incorporated in the cost and emissions calculations.
- The consumption levels and load curves were not varied for the fossil and renewable power plants fleets in order to enable better comparability and to avoid problems associated with the assessment of costs required to serve additional demand in other sectors.

The chosen methodological approach is thus primarily aimed at determining robust cost comparisons between different electricity systems.

2.3. Calculation models used

Various models developed by Oeko-Institut were combined to conduct the analyses undertaken in this study.

The design of the electricity system with a 90 percent renewables share was determined using a simple simulation model. In this model, the residual load and the surplus production from renewable power plants were minimized based on a predefined load curve and the feed-in characteristics of different renewable energy options (in hourly resolution).

The electricity system with a power mix based on fossil fuels was modelled using a simple optimization model, which (using the principle of “perfect foresight”) results in a long-term optimization of the power plant fleet. The output figures for each energy option are calculated based on annual operating times. Operating times were determined based on the cheapest supply option from the full cost perspective for each power plant type. To determine the full cost of fossil fuels for electricity generation, the full cost of making the fuel available was taken into account, i. e. in addition to direct investment, operating and CO_2 costs for lignite power plants, the investment costs and fixed operating costs of open-cast lignite mines were considered.

In terms of the utilization of the power plant fleet, PowerFlex, an electricity market model developed by the Oeko-Institut, was used. PowerFlex is a conventional power plant model that uses the individual elements in the electricity system such as power plants, storage and other flexibility options at lowest cost to fulfil power demand, local and district heating consumption in CHP systems and the need for balancing power. PowerFlex is a mixed-integer, linear optimization model. Its minimizing function includes all the variable costs (marginal costs) of the individual elements. Interrelationships in the energy sector – e.g. the start-up and shut-down of power plants or the provision of balancing power – are taken into account in the model through secondary parameters.

Electricity demand, the electricity feed-in from must-run power plants (e.g. blast furnace gas, waste incineration), electricity feed-in from hydro, wind and photovoltaic power plants, and relevant biogas and sewage gas production are set exogenously in hourly resolution (using the "perfect foresight" approach). By contrast, the quantity of electricity from hydro, wind, biogas and photovoltaic power plants that can actually be integrated into the electricity system is calculated endogenously by the model and depends directly on demand, available flexibility in the system and installed storage capacity. The model version described above covers the European power system but was used exclusively for the analysis of the German power system.

We also carried out a literature review to aid estimation of the cost of grid infrastructure. The need for investment in grid expansion identified from the reviewed literature was used to calculate annuities based on a lifetime of 40 years.

Last but not least, an integration model was developed to determine system costs. In this integration model the power plant fleets, flexibility options (short-term storage, power-to-gas technology) and the grid infrastructure were evaluated in terms of their annualized investment and fixed operating costs. Fuel costs and CO_2 costs and emissions were taken directly from the PowerFlex model.

The annuities of investment costs were calculated using a uniform interest rate of five percent. The planning periods were determined in a technology-specific manner and are shown as such in the following sections. Given the long period of time covered by our analysis, the initial data from the stated sources (with price figures from 2012 to 2015) were not converted to a uniform price. The cost data determined for 2030 and 2050 are thus based on real costs that represent approximately the past four years.

3. Assumptions

3.1. Generation and storage options

3.1.1. Renewable generation options

Two studies conducted on behalf of Agora Energiewende were taken as a basis for the cost assumptions for onshore and offshore wind and photovoltaic plants:

- The cost trends for onshore and offshore wind power plants for 2013, 2023 and 2033 were derived from an analysis carried out by Consentec & Fraunhofer IWES (2013) on the expansion of renewable energy at optimal cost. The data for 2030 were estimated using a linear interpolation. The cost dynamics in 2023 to 2033 were subsequently extrapolated forward to arrive at estimates for 2050. With regard to onshore wind power, the average figures for strong and weak wind turbines were applied.
- The data on photovoltaic costs are based on an analysis conducted by Fraunhofer ISE (2015) on cost trends for ground-based PV plants. These data were then applied to figures on cost trends for rooftop systems, using the structural data reported in Consentec & Fraunhofer IWES (2013). To estimate future developments, an approximately 50 percent increase in the number of roof- and ground-based photovoltaic plants in Germany was assumed.

The capital costs of the power plant fleets operated in 2050 were derived from the cost trends for 2030 to 2050, applying plant lifetimes of approx. 20 years. Here, a roughly linear development was assumed with the result that the capital costs are averages of the calculations for 2030 and 2050.

Table 3-1 shows the assumptions for investment costs and the fixed operating costs and the lifetime/planning period used to determine the annuities of the investment costs.

Since a number of differences can be identified with regard to other analyses conducted on cost developments for renewable generation options (50Hertz 2016, Rech & Elsner 2016, Elsner & Sauer 2015, EIA 2016a, 2016b, NREL 2012), sensitivity analyses of the cost ranges were performed.

Assumptions for costs of electricity generation plants based on renewable energies, 2030 and 2050 — Table 3-1

	Investment costs [€/kW]		Fixed operating costs**	Lifetime [a]	Notes
	2030	2050			
Onshore wind power plants*	957	865	2%	20	Costs converted for 2030 and extrapolated for 2050 based on dynamics of previous decade
Offshore wind power plants	1,920	1,285	2%	20	
Rooftop PV installations	733	491	2%	20	Costs projected on basis of ground-mounted PV installations
Ground-mounted PV installations	651	436	2%	20	

*50/50 mix of strong and weak wind turbines
** Annual costs related to investment costs

Consentec & Fraunhofer IWES (2013), Fraunhofer ISE (2015), calculations and estimates by Öko-Institut

3.1.2. Conventional options for electricity generation

Although a considerable number of conventional power plants have been built in Germany in recent years, substantial uncertainties remain with regard to the specific costs that should be applied to estimates for 2030 to 2050. These uncertainties relate to the future cost of commodities and the future situation on capital markets (especially when one considers the volatility of the past decade).

The cost calculation methods were derived from the data contained in Prognos et al. (2014). The data were extrapolated forward for our analysis using the European Power Capital Costs Index (EPCCI) developed by IHS (2016).

As a general rule, no new cost dynamics were assumed during the periods concerned in this context, meaning that the costs of the power plant fleet in 2050 are drawn from the constant values shown in Table 3-2. Above all, the two natural gas-based technologies should be understood as representative technologies with a specific application and characteristics that could also be realized using other technologies (e.g. modular gas turbine plants).

In some cases, the values in the figure are below the cost figures used in more recent publications (50Hertz 2016, Görner & Sauer 2016, r2b 2014, Frontier & Consentec 2014, EIA 2016a, 2016b). In view of the substantial cost reductions that are assumed in the future for renewable generation plants and flexibility options, a rather optimistic assessment of conventional power trends seemed appropriate and consistent. Nevertheless, sensitivity analyses were conducted in this area as well.

3.1.3. Storage options

In the different development scenarios for a German electricity system that is based extensively on renewable energy, storage options play an important role.

Our empirical analysis is based to large extent on a study of the situation in Germany commissioned by Agora Energiewende (FENES et al., 2014), which considers developments up to 2023 and 2033 and an electricity system with a 90 percent share of renewables. The following assumptions were made when using this data:

- → As a general rule, the averages of the minimum/maximum data were used.
- → The assumptions for 2030 were determined based on a linear interpolation of the data for 2023 to 2033.

Framework assumptions for costs of conventional power plants, 2030 und 2050

Table 3-2

	Investment costs [€/kW]		Fixed operating costs [€/kW]	Lifetime [a]	Notes
	2030	2050			
Lignite power plant	1,600	1,600	40	40	
Hard coal power plant	1,300	1,300	40	40	
Combined cycle power plant	800	800	30	40	
Gas turbine	400	400	10	20	
Hydro power plant	1,000	1,000	40	45	developed site

calculations and estimates by Öko-Institut

- The assumptions used in FENES et al. (2014) for a 90 percent renewables-based system were applied to 2050.
- For pumped-storage power plants, cost approaches taken from our own research and estimates were used; in this connection, we applied data for existing facilities that will be subject to extensive renewal and modernization measures up to 2050.

Table 3-3 shows the framework assumptions for the different storage options. The capacity-related investment costs are derived from the investment costs related to the storage quantities, the respective investment cycles and the costs for the converter (battery storage) and gas storage.

For the power-to-gas option involving synthetic methane, different cost levels were considered for the CO_2 needed. It was assumed that this CO_2 must be made available in a climate-neutral manner, i.e. via the use of biomass or by extraction from the atmosphere:

- In a first case it is assumed that huge technological breakthroughs and corresponding cost reductions are achieved for the extraction of CO_2 from the atmosphere and that these can also be realized in appropriately sized installations. Cressey (2015) reports cost reductions of up to 100 US dollars per tonne of CO_2 in this context. For simplification purposes, 100 euros per tonne of CO_2 was assumed.
- In a second case, substantial technological advances are likewise assumed for the extraction of CO_2 from the atmosphere. However, the costs are expected to fall only to the uppermost level stated in Cressey (2015). Accordingly, a cost estimate of 200 euros per tonne of CO_2 was used. This constitutes a huge cost reduction, given current costs of approx. 600 US dollars per tonne of CO_2 (APS 2011).
- In a third case, it is assumed that the required CO_2 is made available free of charge. In this regard, the carbon released in biomass incineration could be captured. For this to be possible, sufficient quantities of biomass must be available, usage patterns for biomass and power-to-gas generation need to overlap geographically, and plants need to be equipped for the convergence of both processes.

Since there is significant divergence in the projections that have been calculated for storage costs (NREL 2012, Elsner & Sauer 2015, Eichman et al 2016, Feldman et al 2016), we conducted representative sensitivity analyses. Given that considerable uncertainties are associated with not only the cost of CO_2

Framework assumptions for costs of storage options, 2030 und 2050

Table 3-3

	Investment costs [€/kW]		Fixed operating costs*	Lifetime [a]	Notes
	2030	2050			
PtG plants H_2	871	494	2%	25	costs converted for 2030, costs for gas storage included in investment costs
PtG plants synCH_4	959	629	2%	25	
Battery storage	948	641	2%	25	costs converted for 2030, including converter
Pumped storage power plant	1,000	1,000	40	45	developed site
*Annual costs related to investment costs, for pumped storage power plants in €/kW					

FENES et al. (2014), calculations and estimates by Öko-Institut but also its availability for the production of synthetic methane (Oeko-Institut 2014), additional sensitivity analyses were carried out for a scenario in which the power-to-gas option is limited to the production and use of hydrogen.

3.2 Grid infrastructure

The cost of grid infrastructure was determined using two different approaches, one for a fossil-fuel system and one for a renewables-based system. Only the electricity grid was considered; gas grid investments that may become necessary were not taken into account for simplification purposes.

The total costs of grid infrastructure were first estimated based on the grid charges assessed to different user groups, as per the classification system used in the monitoring reports of the German Federal Network Agency and the German Federal Cartel Office (BNetzA & BKartA 2016). Considering electricity sales in 2010 amounting to 142 terawatt hours to households, 137 terawatt hours to the service sector and 212 terawatt hours to the industry and transportation sectors (excluding on-site generation), we arrive at an annual total system cost of 18.2 billion euros.

Given the fact that there will also be slight cost increases for grid infrastructure with an energy system based on fossil fuels, a cost increase of 10 percent was assumed for 2050; this percentage was determined based on estimates made within the scope of the Energy Roadmap 2050 (EC 2011a, 2011b) for scenarios without additional climate protection ambition. Overall, for electricity systems in 2050 that are based extensively on fossil fuels, our calculations yield annual grid infrastructure costs of approx. 20 billion euros.

For the renewables-based system, this base level was increased by the annuities of investment costs that are attributable solely to renewables for expanding power grids, including the connection of offshore wind power. The projections made available to date for the period up to 2035 result in different estimated ranges:

- → An analysis conducted by 50Hertz (2016) on the transmission grid expansion needed to achieve climate protection targets up to 2035 yields an investment cost range of 30 to 35 billion euros.
- → Based on the most recent estimates of the need for investment in transmission grids (which take into consideration underground cabling), a cost range of 27 to 34 billion euros has been calculated for the period up to 2025 based on the current draft of Germany's Grid Development Plan (second draft of the Grid Development Plan Strom 2025, 50Hertz et al. 2016a).
- → Calculations made on the basis of estimates provided in the most recent draft of the offshore grid development plan (50Hertz et al., 2016b) result in an estimated investment volume of approx. seven to ten billion euros for the connection of offshore wind parks to the grid by 2025.
- → According to the analysis of grid expansion costs conducted within the scope of the IMPRES project of German Federal Ministry for the Environment (Fraunhofer ISI 2014), investment costs of 15 to 20 billion euros for the transmission grid, 10 to 12 billion euros for the connection of offshore wind, and 18 to 27 billion euros for distribution grids will be required up to 2022.
- → In a long-term analysis conducted by P3 Energy & IFHT (2012), expansion costs for the transmission grid up to 2050 are estimated at 31 to 39 billion euros; these estimates include substantial costs for the expansion of cross-border interconnectors but exclude additional costs for extensive underground cabling. Without the interconnectors, which depend strongly on power system development trends in the countries concerned, the expansion costs are 21 to 25 billion euros.
- → A study commissioned by the German Federal Ministry for Economic Affairs and Energy (E-Bridge et al. 2014) estimates distribution grid expansion costs of 23 to 49 billion euros in 2013–2032. The upper range is based on a scenario that assumes very rapid expansion of renewable energy (installed capacity of over 200 gigawatts in 2032); aside from this (extreme) scenario, invest-

ment costs of 23 to 28 billion euros are estimated. However, the study estimates that technological advancements will reduce these costs by at least 20 percent.

- A distribution grid study conducted by Dena (2012), estimates investment costs of 22 to 27.5 billion euros by 2030.
- The distribution grid study commissioned by the German Association of Energy and Water Industries (E-Bridge et al. 2011) calculates investment costs up to 2020 of 21 to 27 billion euros, which can be reduced to 20 to 26 billion euros when technological advancements are applied.

A number of different influencing factors have to be considered in the projections based on these data:

- Almost all studies show that the need for investment decreases in the run-up to 2030; the largest need for grid investment will occur in the next ten years.
- For the period after 2030, other flexibility options (such as storage) will play a larger role over time in light of the continued expansion of wind and solar power generation; the need for grid expansion is thereby not avoided, but decreases further over time.
- All analyses show that technological advances in grid expansion will also enable substantial cost decreases.

Taking into account these factors, the following assumptions are made for our subsequent analysis:

- For the expansion of the transmission grids up to 2050, an investment level of 60 billion euros was chosen; applied to a 40-year period, this yields in an annuity of 3.5 billion euros, assuming an interest rate of five percent. By contrast, we arrive at an annuity of 4.7 billion euros when assuming higher investment costs as part of a sensitivity analysis.
- Total investments of 30 billion euros are assumed for the connection of offshore wind power plants to the grid up to 2050; this corresponds to an annuity of 1.7 billion euros. By contrast, we arrive at an annuity of 2.3 billion euros when assuming higher investment costs as part of a sensitivity analysis.
- Total investments of 40 billion euros are assumed for the expansion of distribution grids up to 2050, which corresponds to an annuity of 2.3 billion euros. We arrive at an annuity of 4.7 billion euros when assuming higher investment costs as part of a sensitivity analysis.

We thus estimate that total grid infrastructure costs will equal approx. 7.6 billion euros annually, with costs potentially ranging as high as 11.7 billion euros annually. However, it must be noted that our rough estimate approach is likely to overestimate rather than underestimate the additional costs of an electricity system based on renewables.

Last but not least, a plausibility check was undertaken on the cost differences for infrastructure by reviewing analyses conducted for the EU Energy Roadmap 2050 (EC 2011a, 2011b). Our figures are comparable to the estimated cost differential between the high renewables and reference scenarios.

3.3. Costs for fuels and emission allowances

Assumptions concerning cost trends for fossil fuels and emission allowances are the key determinants of the volume of generation from fossil fuel power plants. The following estimates are used:

- For lignite, we assume full costs of 6 euros per megawatt hour of fuel. This includes 1.5 euros per megawatt hour for the costs of short-term provisioning (the key factor determining operation), and 4.5 euros per megawatt hour to cover the full costs of opencast mining, which can only be reduced over long (and varying) periods of time;
- For natural gas prices, we considered both high and low price trends:
  - In a low-price scenario, we estimate power plant prices of approx. 14.9 euros per megawatt hour

(including transport and assuming the lower heating value), which approximately corresponds to the prices at the beginning of 2016;
  - In a high-price scenario, the natural gas price increases to 42.1 euros per megawatt hour including transport; this corresponds to the level expected in the long term in many mainstream projections (e.g. IEA 2016).

→ Two developments were also analysed for the price of imported steam coal (hard coal), including transport:
  - In a low-price scenario, the price remains at 5.4 euros per megawatt hour including transport, which corresponds to the level at the beginning of 2016; and
  - In a high-price scenario, which assumes generally increasing prices for fossil fuel exports and imports, the price amounts to 15.4 euros per megawatt hour. This corresponds approximately to the upper range of current mainstream projections (IEA 2016).

→ In terms of the costs of emission allowances, three different developments are examined.[1]
  - In a low-price scenario, the price remains at 20 euros per emission allowance (European Union Allowance, or EUA); this scenario showcases the effects that will occur if the system fails to generate scarcity prices in the long term (either due to a continued surplus of emission allowances or an extensive supply of emission allowances from outside the EU).
  - In a high-price scenario, the price rises to 103 euros per emission allowance. This scenario assumes ambitious climate policy efforts in which CO_2 pricing plays an important role (Oeko-Institut & Fraunhofer ISI 2015) and in which there are no policy interventions in the EU ETS during high scarcity prices.
  - In a medium price scenario, scarcity arises in the EU ETS; however, the price increase is limited through price limits or similar mechanisms to 50 euros per emission allowance.

3.4 Electricity demand

The potential development paths for the power plant fleet that are examined here all presuppose the same underlying demand structures, in line with the considerations set forth in section 2.2.

Net electricity consumption (i. e. domestic final consumer demand in addition to grid losses) amounts to 550 terawatt hours in all scenarios. The on-site consumption by power plants and the electricity fed into storage are not incorporated in final demand but are, of course, taken into account within the electricity supply system.

The demand figure of 550 terawatt hours was obtained from a projection in which additional electricity demand from the heating and transportation sectors does not substantially exceed the energy efficiency gains in traditional power applications (Climate Protection Scenario 80 of the Climate Protection Scenarios 2050, Oeko-Institut & Fraunhofer ISI 2015). In a development without significant efforts to increase the energy efficiency of traditional power applications, which can be assumed without taking into account ambitious climate protection targets, a similar level of electricity demand would arise.

In our estimates, the development of demand over time corresponds to the historically observed trend in 2011. This year also serves as a basis for modelling the electricity supplied by renewable energy power plants.

1 It should be noted at this point that the damage costs lie substantially above these levels. As a result, UBA (2014a) recommends a price of 80 (40–120) euros for the short term, 145 (70–215) euros for the medium term and 260 (130–390) euros in the longer term per tonne of CO_2 (compared to 2010 prices). In the cost-benefit analyses of the current German Federal Transport Infrastructure Plan (PTV et al., 2016) a cost approach of 145 euros per tonne of CO_2 is used. The UK government (DECC 2015) uses CO_2 costs of 100 (50–150) euros per tonne of CO_2 (at 2015 prices) for policy planning.

4. Results

4.1 Overview of the electricity generation systems considered

For the two systems based extensively on renewable power plants for electricity generation, we arrive at the following renewable power plant fleet for 2050:

- → 4.5 gigawatts of hydro
- → 130 gigawatts of onshore wind power
- → 40 gigawatts of offshore wind power
- → 90 gigawatts of photovoltaics
- → 2.4 gigawatts from other renewable energy power plants (biomass, geothermal)
- → 3.8 gigawatts from other fossil fuel power plants (blast furnace gases, etc.)
- → 9 gigawatts of pumped storage power plants (including pumped storage power plants in Germany, the Vianden pumped storage power plant in Luxembourg and the pumped storage power plants in Austria controlled by German suppliers).

The two renewable electricity systems are distinguished by the necessary flexibility options (the higher value becomes necessary when the power-to-gas flexibility option has a large share):

- → 45 and 49.5 gigawatts from combined cycle power plants (mostly for generation from power-based gas, depending on the expansion of short-term storage);
- → 15.4 and 37.9 gigawatts from gas turbines (to guarantee security of supply when weather years make this necessary, and mostly to generate electricity from power-based gas if the expansion of short-term electricity storage allows this);
- → 26 and 35.7 gigawatts from the connected capacity of power-to-gas plants (depending on the expansion of short-term storage);
- → 27 gigawatts from new (battery) short-term storage in the scenario with a high share of short-term storage; in the scenario without this additional short-term storage, these 27 gigawatts do not apply.

Overall, an installed capacity of 390 to 400 gigawatts results for the developments of electricity systems based on renewable energy, of which approx. 105 gigawatts are in power plants that can definitely provide secured capacity.

Figure 4-1 shows the two electricity systems based extensively on renewable energy alongside the two electricity systems based extensively on fossil fuels:

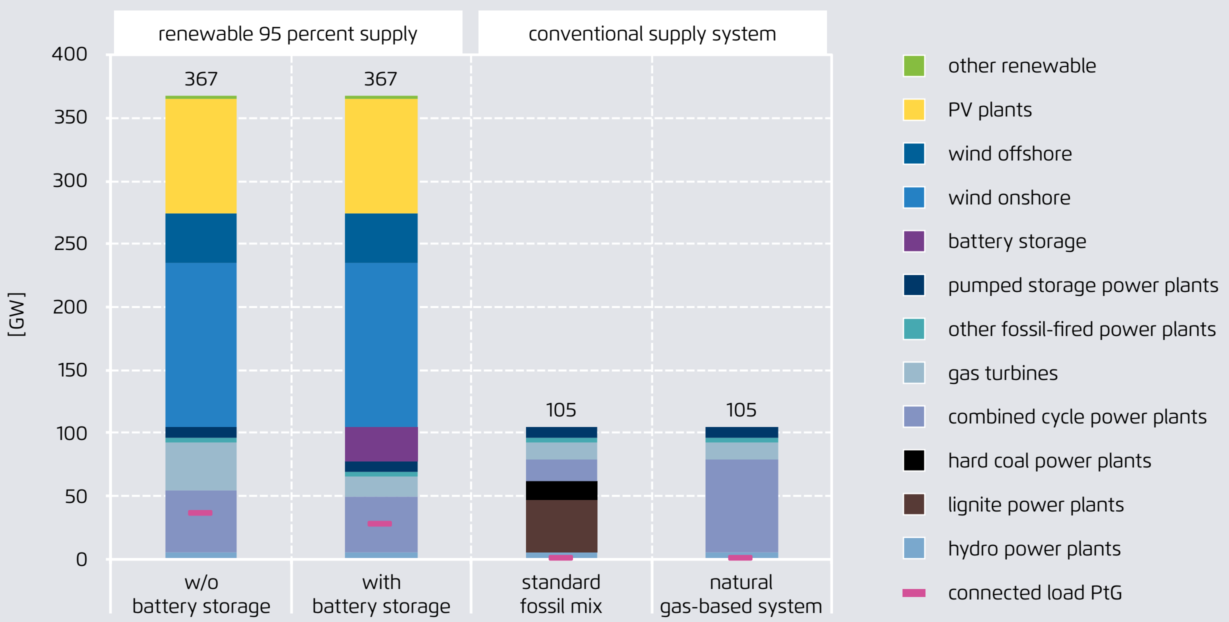
- → The "coal-based system" scenario describes a development that would arise on a full cost basis for a system without wind, solar and biomass energy if the level of climate policy ambition remains low. Such a power plant fleet for electricity generation determined using the stated framework conditions remains within the conventional structure of basic load, medium load and peak load power plants that has arisen in the past (but including nuclear power). In addition to must-run plants and hydroelectric power plants (3.8 gigawatts and 4.5 gigawatts), lignite power plants (41.7 gigawatts) are mainly operated as basic load power plants. Periods of medium system load are fulfilled by coal-fired power plants (15.2 gigawatts) and combined cycle power plants (17.6 gigawatts) while 12.9 gigawatts of power from gas turbines and 9 gigawatts from pumped storage power plants cover peak load demand.
- → In the electricity system with a natural gas-based power plant fleet, it is assumed that uncertainties about future climate policy and/or very optimistic expectations for natural gas prices lead to a situation in which investments in CO_2-intensive lignite and hard coal power plants are halted, with the associated loss in power plant capacity being replaced with combined cycle power plants. All other assumptions are identical to the coal-based electricity system.

Both electricity systems based on fossil fuels thus constitute two extreme scenarios for Germany marked by the absence of power generation from wind, solar, biomass, or nuclear. It should be noted that the two development scenarios for an electricity system based extensively on fossil fuels are not independent of the framework conditions for fuel and, in particular, CO_2 prices. For the sake of clarity, however, we analyse all variants of the power plant mix for the entire range of the framework assumptions. In the discussion of the results, however, issues of consistency are addressed.

Sensitivity analyses were also conducted for the fossil-based electricity systems with a development path in which a limited expansion of wind and solar power plants occurs in the context of high fuel and CO_2 prices and within a market design that does not specifically consider the revenues of power generation plants based on fluctuating renewable energy. However, this expansion is also clearly circumscribed under the framework conditions, as the revenues of wind and solar are reduced by the merit order effect.

Figure 4-2 shows that even in a market environment with high fuel and CO_2 prices the installed capacity of wind and solar power plants remains below 80 gigawatts, which corresponds to approx. one-third of total electricity generation in Germany. It is assumed in the sensitivity analyses that the expansion of wind and solar electricity generation does not necessitate an additional expansion of grid infrastructure or storage options.

Installed net capacity of example power plant fleets, 2050 — Figure 4-1



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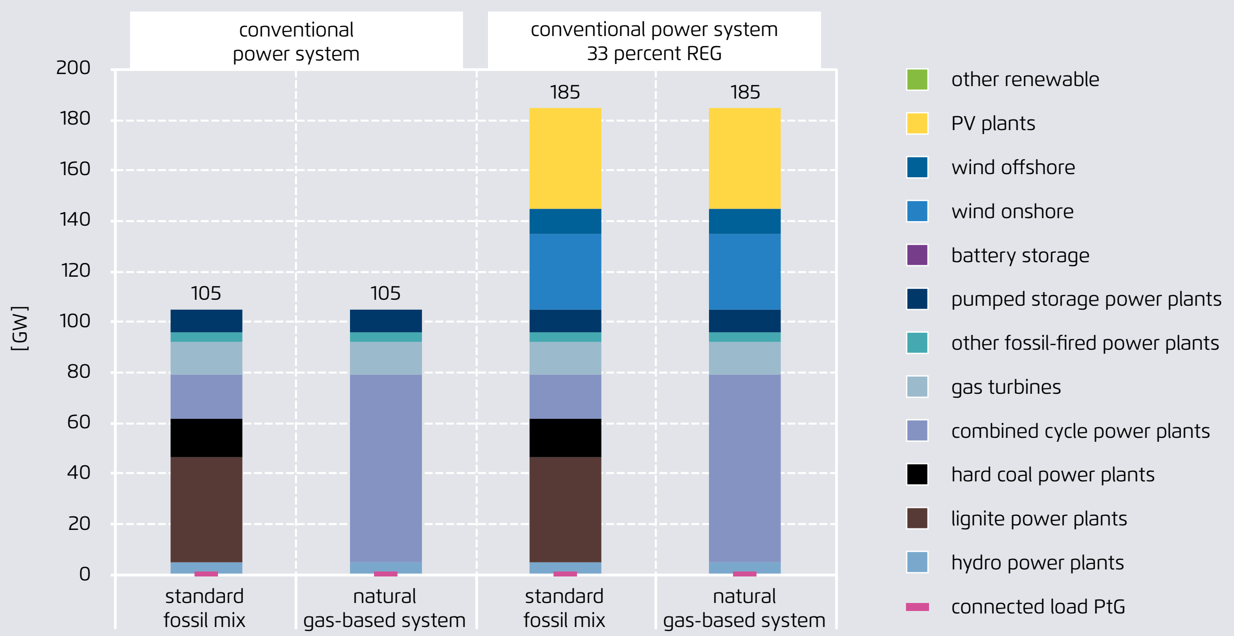
Installed net capacity of example fossil power plant fleets with limited expansion of wind and solar power plants and in context of high fuel and CO_2 prices, 2050

Figure 4-2



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4.2. Analysis of electricity supply systems based on renewable energy

4.2.1. Electricity generation and CO_2 emissions

Both renewables-based systems serve over 95 percent of electricity demand with power plants based on renewable energy and reduce the greenhouse gas emissions of the electricity sector by approx. 96 percent compared to 1990. The two system designs make divergent use of flexibility options, however:

- → In the scenario without battery storage, the total electricity generation from renewable energy amounts to 622 terawatt hours; in addition, 42 terawatt hours of electricity are generated in gas-fired power plants operated with power-based gases. The electricity generated with power-to-gas amounts to approx. 109 terawatt hours; the power-to-gas plants are used for approx. 3,040 full load hours. Approx. 36 terawatt hours of electricity are generated by additional applications outside of the (traditional) electricity sector or for curtailment.
- → In the scenario with substantial battery storage capacities, the total electricity generation from renewable energy likewise amounts to 622 terawatt hours, but electricity generation from gas-fired power plants using power-based fuels is considerably lower, at 32 terawatt hours, than in the scenario without battery storage. Eighty-three terawatt hours are used for the production of power-to-gas; the utilization of power-to-gas plants is, at about 3,200 full load hours, approx. five percent higher than in the scenario without battery storage. Fifty terawatt hours from surplus electricity generation based on renewable energy remains for additional power applications or for curtailment.

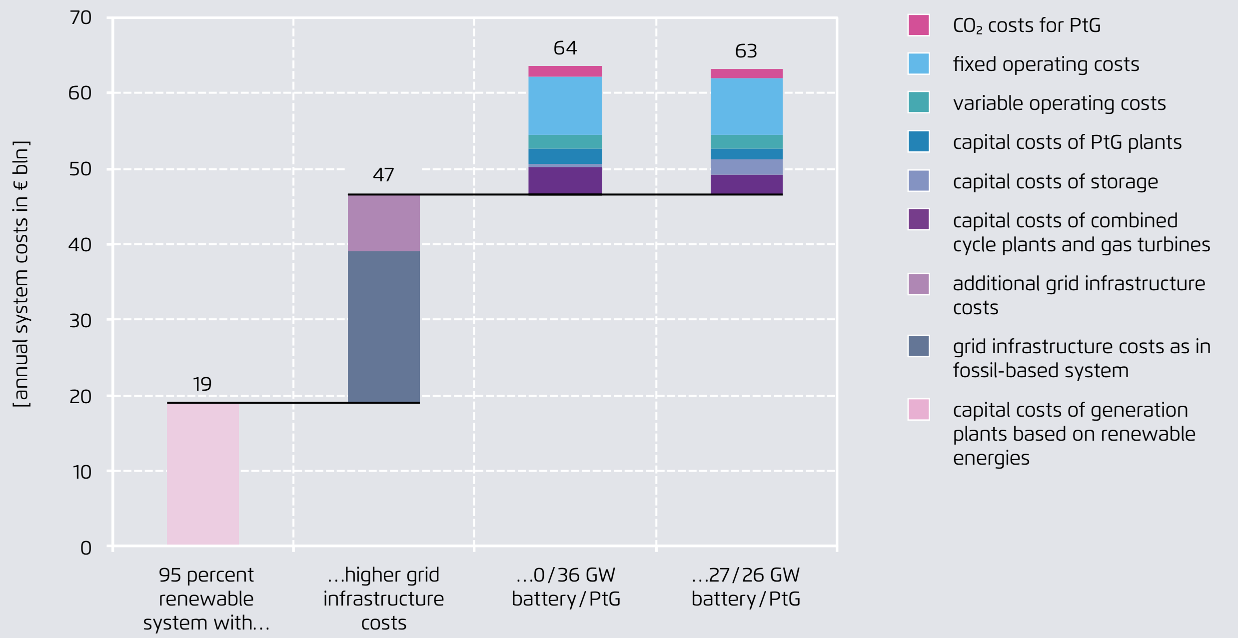
In both scenarios, there is surplus electricity that can be made available for additional electricity applications and which lead to cost savings in the relevant sectors. Against the background of substantial uncertainties in the economic assessment of these system effects and for the purpose of keeping our estimates conservative, the cost effects that go beyond the boundaries of the traditional electricity system were not taken into account in our subsequent cost analyses. However, the cost effects that may go beyond the boundaries of the power sector would tend to be larger in an electricity system with significant shares of battery storage than in a system in which flexibility options are mainly based on power-to-gas.

4.2.2. System costs

Figure 4-3 shows the total system costs of both German electricity system designs with a 95 percent share of renewable energy:

- → The annual capital costs for renewable energy power plants amount to approx. 19.1 billion euros.
- → The annual electricity grid costs amount to approx. 20 billion euros and increase by approx. 7.6 billion euros to 27.6 billion euros due to the grid requirements of a renewables-based system.
- → The fixed operating costs of the electricity system amount to approx. 7.7 billion euros.
- → The variable operating costs of the electricity system amount to approx. 1.8 billion euros; for the procurement of climate-neutral CO_2, additional costs of 1.5 billion euros arise in the system design without additional short-term storage and 1.2 billion euros in the design with a significant battery storage share.
- → In the scenario without battery storage, the capital costs of electricity storage amount to approx. 0.5 billion euros and in the scenario with 27 gigawatts of battery storage they amount to approx. 2.0 billion euros.
- → The capital costs of power-to-gas plants amount to 2.0 billion euros and in the scenarios with substantial battery storage capacities to 1.5 billion euros in the system design without battery storage.

Total system costs of electricity systems based extensively on renewable energies, 2050 — Figure 4-3



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- The capital costs of natural gas power plants (combined cycle power plants and gas turbines) for generating electricity from synthetic gas and/or for guaranteeing security of supply amount annually to approx. 3.5 billion euros in the design without battery storage and 2.6 billion euros in the design with 27 gigawatts of battery capacity.

Capital costs thus represent the vast majority of costs in these electricity system designs. Of the total costs, which differ only slightly – amounting to 63.7 billion euros in the design without battery storage and 63.3 billion euros in the design with substantial battery storage capacities – only five percent of costs are variable costs (variable operating costs and the procurement of climate-neutral CO_2) and only twelve percent of costs are fixed operating costs.

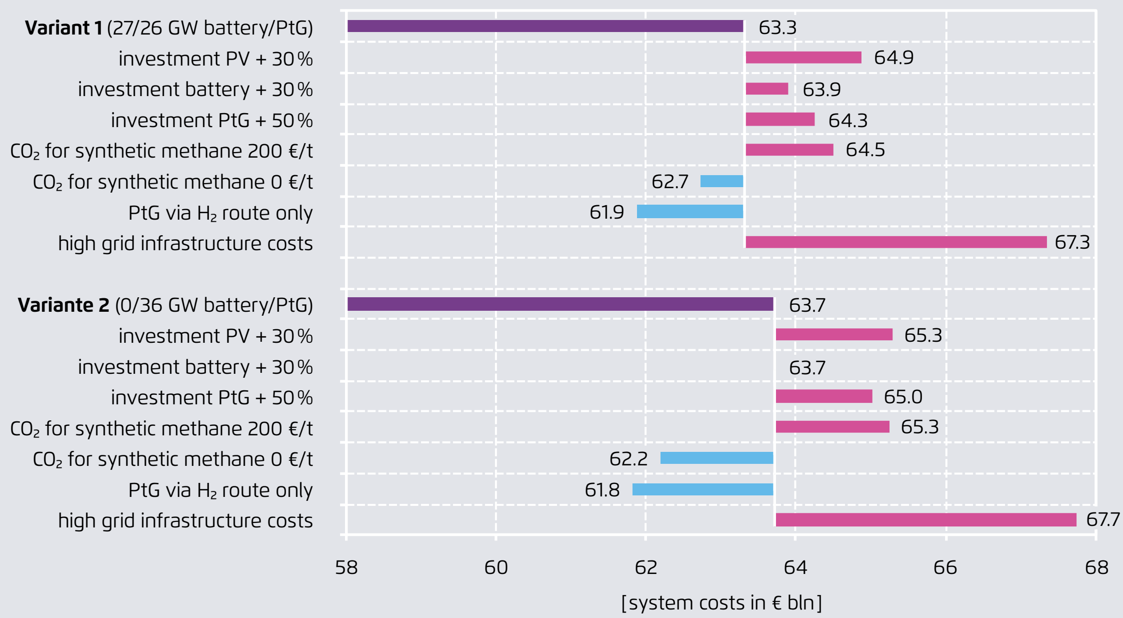
Considering the high share of capital costs (over 80 percent), a closer assessment of uncertainties in our calculation methods is very important.

Figure 4-4 shows the results of a number of sensitivity calculations conducted for assumptions particularly relevant to the uncertainties:

- If the pace of investment cost reductions for photovoltaics is slower than that assumed by Fraunhofer ISE (2015) and investment costs arise that are approx. 30 percent higher than the reference levels, the total system costs increase by approx. 1.6 billion euros, i. e. by 2.5 percent. A corresponding cost reduction would result if photovoltaic costs are 30 percent lower than those stated in Fraunhofer ISE (2015) and fall within the lower ranges calculated by 50Hertz (2016).
- If the pace of cost reduction in short-term storage (i. e. batteries) is slower than assumed in FENES et al. (2014) and investment costs arise that are 30 percent above the reference levels, the system costs in the second design of the renewable electricity system increase by approx. 0.6 billion euros, or 0.9 percent.

Sensitivity calculations for system costs of power systems based extensively on renewable energies, 2050

Figure 4-4



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- If the achievable cost reductions in power-to-gas plants are lower than those assumed in the especially optimistic forecasts presented by FENES et al. (2014) such that cost levels in 2030–2050 are 50 percent higher than the reference levels, then system costs increase by 1.3 percent (Scenario 1), or 0.9 billion euros. This corresponds to a cost increase of 2.0 percent (Scenario 1) and 1.5 percent (Scenario 2) compared to the system costs of the reference cases.
- If the costs for making climate-neutral CO_2 available for synthetic methane amount to 200 rather than 100 euros per tonne of CO_2, the operating costs of the electricity system based on renewable energy are 1.5 billion euros (Scenario 1) and 1.3 billion euros (Scenario 2) higher, respectively. This corresponds to an increase in system costs amounting to 2.4 percent and 1.9 percent.
- In the event that climate-neutral CO_2 is available free of charge for the production of synthetic methane (e.g. as a waste product of large-scale biogas production), the system costs are 1.5 billion euros (Scenario 1) and 0.6 billion euros (Scenario 2) lower, respectively. These levels are 2.4 percent and 0.9 percent below the respective reference scenarios.
- In a system with synthetic gas produced only via the hydrogen route and which omits the methanization stage, the costs are 1.9 billion euros lower in Scenario 1 and 1.4 billion euros lower in Scenario 2. This corresponds to a 3.0 percent and 2.3 percent reduction in the total costs, respectively.
- If the costs of grid infrastructure develop according to the high cost scenario, the annual system costs increase by 4 billion euros, which corresponds to a cost increase of 6.3 percent.

From an overall perspective, the two following uncertainties arise for the development of the total costs of a renewable electricity system:

- Of the different areas for which significant uncertainties may arise (investment costs, production of climate-neutral CO_2, etc.), power-to-gas involves special uncertainties, although it should not be assumed that these uncertainties always increase costs.
- Larger uncertainties remain with respect to electricity grid infrastructure and their additional costs, although development scenarios are also conceivable in which the grid expansion costs could be substantially reduced, especially in the case of distribution grids.

The system cost comparison shows that the differences and uncertainties relating to storage options mostly stem from the capital costs of the renewable power plants and the additional costs of grid infrastructure. The gas-fired power plants – the utilization of which may become necessary to guarantee security of supply – only have a minor influence on total system costs.

4.3. Analysis of electricity supply systems based on fossil fuels

4.3.1 Electricity generation and CO_2 emissions

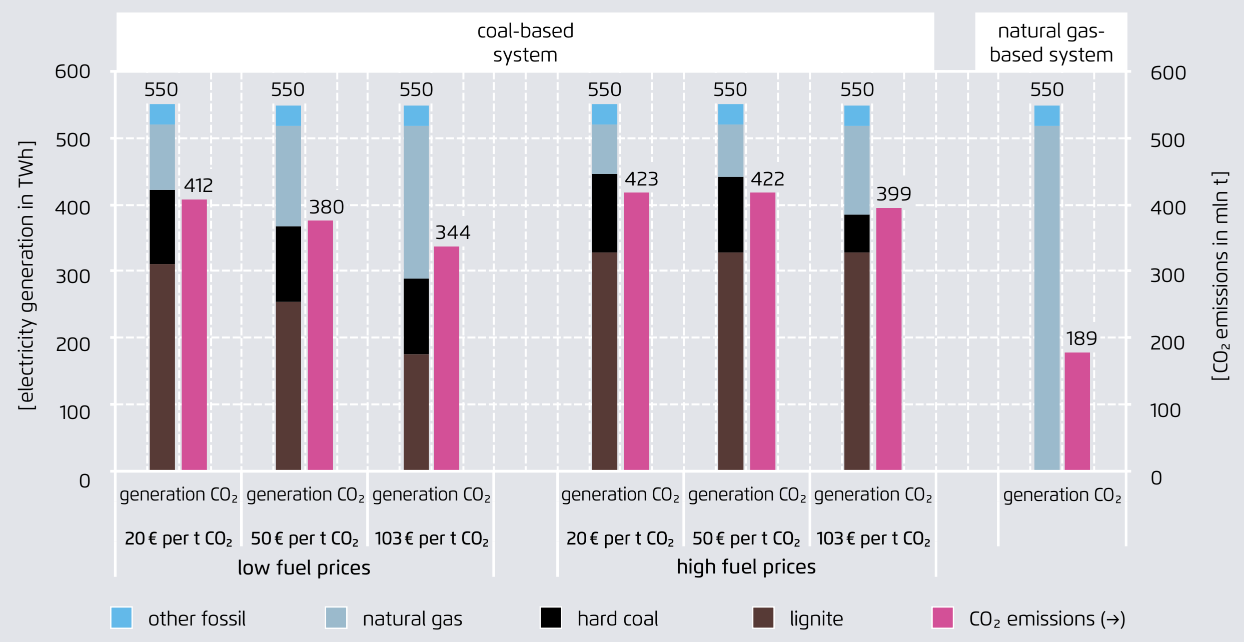
The electricity system designs based extensively on fossil fuels lead to very different generation patterns and CO_2 emissions when divergent assumptions regarding fuel and CO_2 prices are considered (Figure 4-5).

For the coal-based system with conventional fuel profiles for basic, medium and peak loads, the following results:

- The structure of electricity generation is largely determined by the underlying assumptions for fuel and CO_2 prices. In the scenarios with low fuel prices, the CO_2 price has a substantial influence, particularly on the share of natural gas and lignite in power generation. In the case of high energy prices, significant changes in the generation mix only arise in the scenario with very high CO_2 prices and with a view to the share of natural gas and hard coal in power generation. Overall, high hard coal and natural gas prices tend to result in higher levels of electricity generation from lignite power plants.

Electricity generation and CO_2 emissions of different fossil-based power systems, 2050

Figure 4-5



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→ Against this backdrop, emission reductions remain low. In the scenarios with low fuel prices, the emission reductions are between 10 percent and 24.5 percent compared to 1990 (when the emissions of German electricity generation were approx. 456 million tonnes of CO_2); with a CO_2 price of 50 euros per emission allowance, an emission reduction of approx. 17 percent arises. Only for the rather unlikely scenario with high fuel prices do emission reductions of 12 percent result; otherwise the emission reduction amounts to approx. 7 percent compared to 1990.

For an electricity system based extensively on natural gas (the least CO_2 intensive fossil fuel), a different situation arises:

→ Fuel and CO_2 prices do not change the power generation mix; there is only a slight optimization between natural gas-fired combined cycle power plants and gas turbines.

→ Correspondingly, the emission reduction compared to 1990 levels is substantially higher at 59 percent and is generally unaffected by variations in fuel and CO_2 prices. This scope of reduction is still far from meeting German reduction targets, however.

With a view to the resulting emission levels, four important conclusions can be drawn:

→ All resulting emission levels for the electricity sector are far from meeting the emission reduction targets for 2050 set forth in Germany's Energy Concept (BMWi 2015).
→ The long-term and capital-intensive investments made in electricity generation have a considerable effect on the achievable emission reductions, even when a very high CO_2 price is assumed.
→ In addition to the capital stock established by 2050, conditions on domestic and international energy markets have a substantial influence on the

achievable emission reductions, even with a very high CO_2 price.

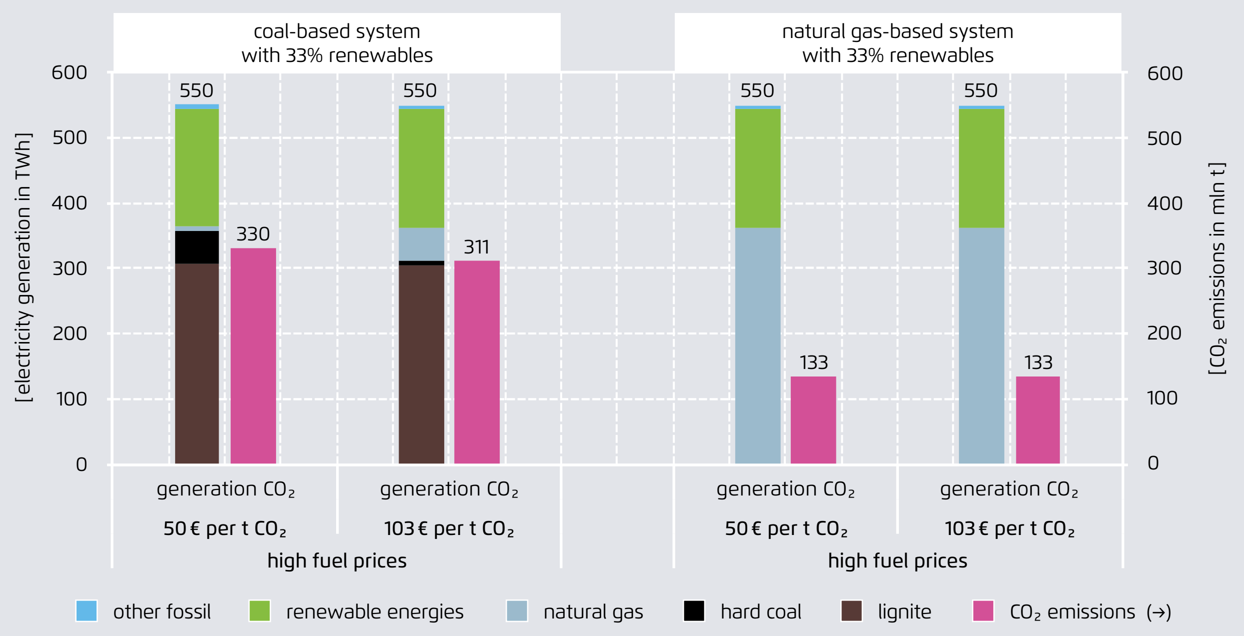
→ CO_2 pricing has an effect on emission reductions above all in a market environment with low fuel prices.

In the classification of these results, it should be taken into account that with a very CO_2-intensive capital stock and very high CO_2 prices, the power plant fleet would adapt in reality (i. e. for economic reasons, coal-fired power plants would be taken off the grid at an early stage or would not be built). This can only be incorporated in the present statistical analysis via the comparison with other scenarios (see below). However, it also clearly shows the path dependencies of the system and the large uncertainties surrounding the market conditions that are crucial to the achievable emission reductions. At the same time, it is clear that the possibilities are very limited for counteracting this development within a few decades through realistic CO_2 prices (irrespective of the mechanism used to generate such prices).

Figure 4-6 shows the situation when high fuel and CO_2 prices arise in the 2030 to 2050 period and investments in renewable energy arise on this basis without the need for financing mechanisms and in a way that does not hugely erode the profitability of renewable power plants within an electricity system based extensively on fossil fuels.

Electricity generation from renewable energy reaches a 33 percent share. Compared to the 1990 base levels in the coal-based system, the CO_2 emissions decrease by 27.5 percent (assuming CO_2 prices of 50 euros per emission allowance) and 32 percent (assuming CO_2 prices of 103 euros per emission allowance). For renewable energy combined with a power plant fleet that is almost completely based on natural gas, the emission reductions amount to approx. 71 percent.

Sensitivity analysis for electricity generation and CO_2 emissions of different fossil-based power systems with limited share of renewables, 2050 — Figure 4-6



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4.3.2. System costs

An analysis of the system cost structures for a system based mostly on a traditional mix of lignite and hard coal as well as natural gas (Figure 4-7) yields the following results:

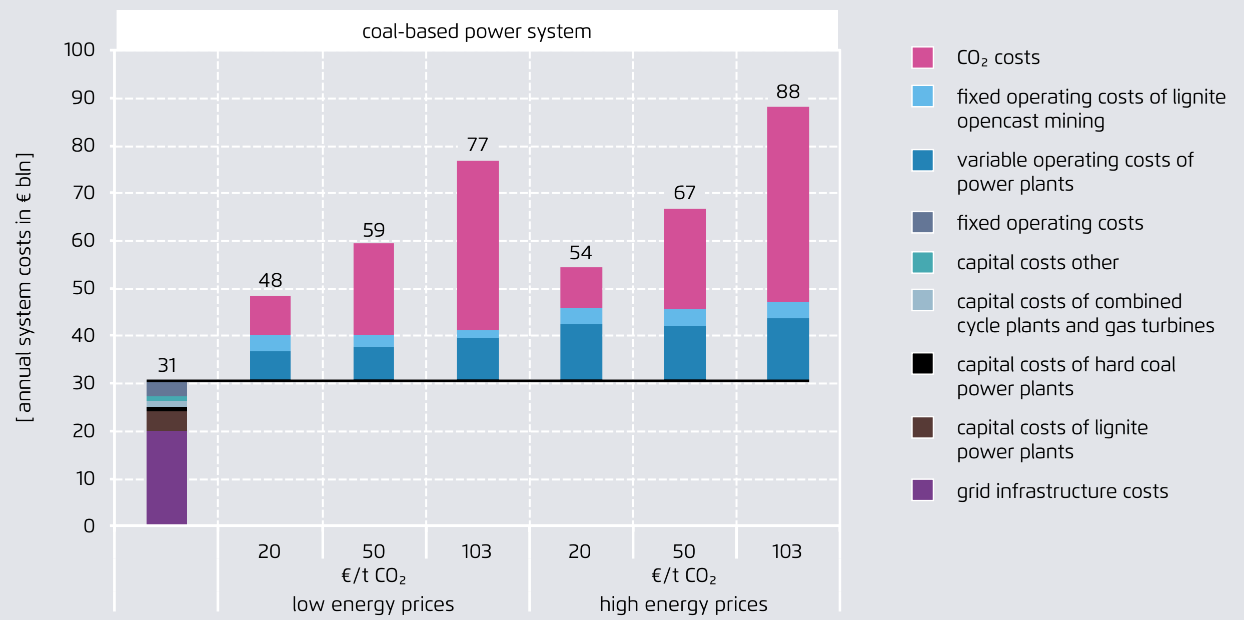
- In terms of capital costs, approx. two-thirds of the total system costs are attributable to grid infrastructure. The capital costs for fossil fuel power plants make up the smaller share, amounting to approx. ten billion euros a year.
- Fuel costs range between 6.4 to 13.4 billion euros, depending essentially on the fuel and CO_2 market environment.
- The fixed costs of opencast lignite mining amount to approx. 2 to 3.5 billion euros a year; the higher amount occurs in an environment marked by high fuel prices and/or very low CO_2 prices.
- The limited responsiveness of the power plant fleet to the dynamic increases in CO_2 prices is also reflected in the large role played by CO_2 costs, which have a particularly strong influence on the system costs and can reach shares of 46 percent and above when high CO_2 prices are assumed.

For an electricity system based substantially on natural gas and the achievement of medium emission reductions (Figure 4-7), the following results arise:

- The capital costs of the system are slightly lower than for the scenario with a fossil fuel (coal/natural gas) mix. This is only the case, however, when it is assumed that an electricity system based almost completely on natural gas does not lead to substantial additional infrastructure costs. In any case the grid infrastructure costs amount to approx. one-third of the total capital costs for the electricity system. It should be noted, however, that potentially higher natural gas infrastructure costs are not taken into account.
- The variable costs of the natural gas-based system are directly proportional to the assumptions con-

Total system costs of coal-based electricity system dependent on CO_2 costs and fuel prices, 2050

Figure 4-7



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cerning fuel and CO_2 prices, to which the system can only react to an extremely limited extent.

- The fuel and CO_2 costs have a substantially larger share of the total system costs, when high fuel and/or high CO_2 prices are assumed.

From a cost perspective alone and without taking into account the achievable emission reductions, a natural gas-based electricity system leads to lower system costs than the conventional coal-based system only in the scenarios with low fuel prices and high fuel and high CO_2 prices. In the system cost comparison for the same assumptions for fuel and CO_2 prices, the cost differential between the two fossil-based systems is highly assumption-sensitive. With a view to differences in emission reductions, these costs range from -107 euros per tonne of CO_2 (low fuel/high CO_2 prices) to 63 euros per tonne of CO_2 (high fuel/low CO_2 prices).

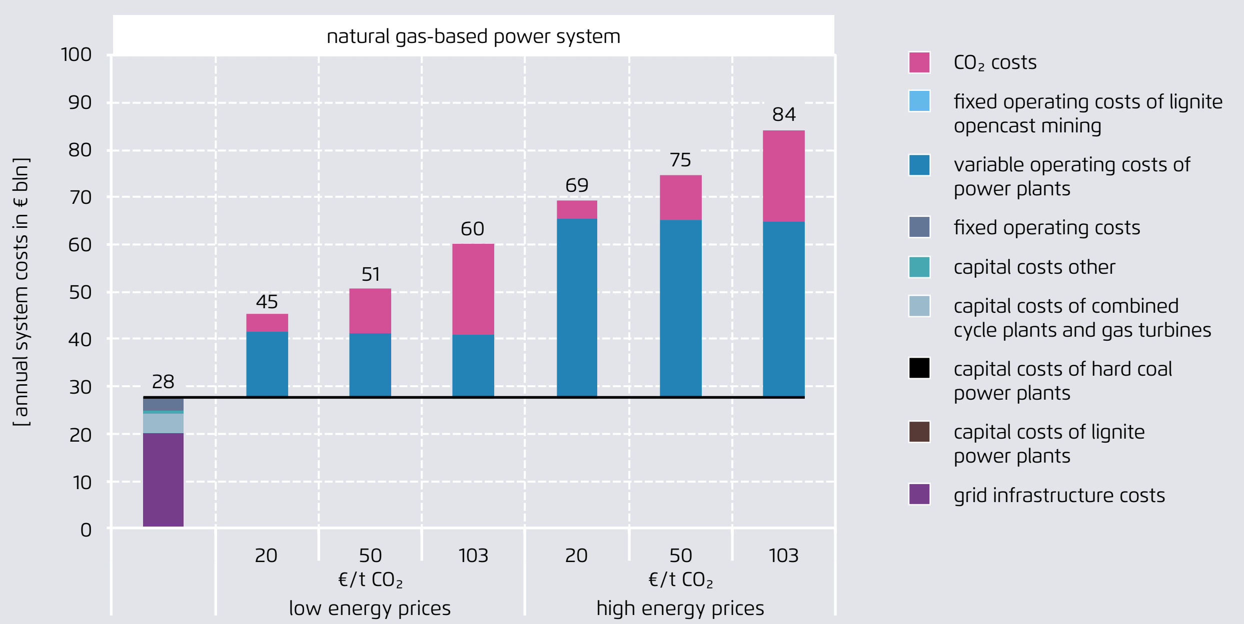
A number of sensitivity analyses were carried out for the development paths of fossil-based electricity systems.

First, we analysed the effects of higher investment costs for lignite and hard coal-fired power plants. Assuming that the investment costs are 20 percent above those assumed in the reference cases (see Section 3.1.2), annual system costs are approx. one billion euros higher, corresponding to a 1 to 2 percent increase in the total system costs (the higher value arises above all when low fuel and CO_2 prices are assumed).

Figure 4-9 shows the results of sensitivity analyses with respect to total system costs when the revenues of wind and solar power plants can trigger at least a minor expansion of renewable electricity generation, when high fuel and CO_2 prices are assumed.

Total system costs of natural gas-based power system dependent on CO_2 costs and fuel prices, 2050

Figure 4-8



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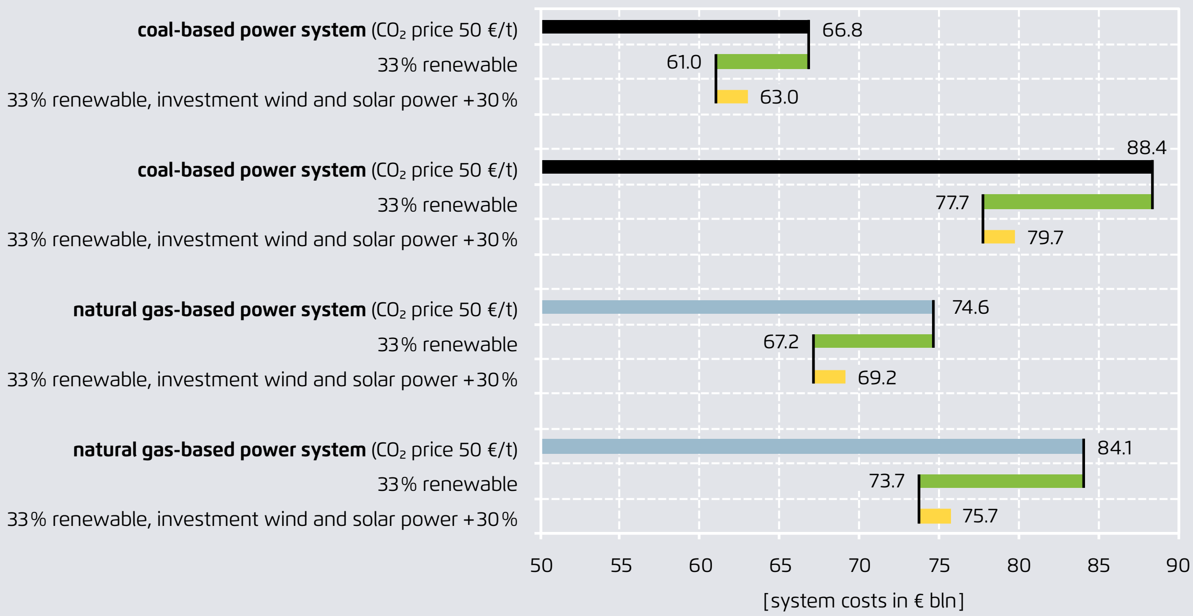
Sensitivity analyses for system costs of different fossil-based power systems with limited share of renewables and in context of high energy prices, 2050

Figure 4-9



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In all scenarios, total system costs decrease by 10 to 12 percent, provided wind and solar cost reductions follow the path assumed for the renewables-based systems. In a final analysis, this would mean that the international expansion of renewables continues unabated and is only curtailed strongly in Germany. Since such a situation does not seem especially plausible, we assessed one more variation of the parameters. It was assumed that the investment costs for wind and solar power plants are 30 percent higher than in the reference cases. This decreases the system-cost effects by 2 to 3 percentage points, such that system costs are only 6 to 10 percent lower than in the fossil-fuel scenarios without any wind or solar.

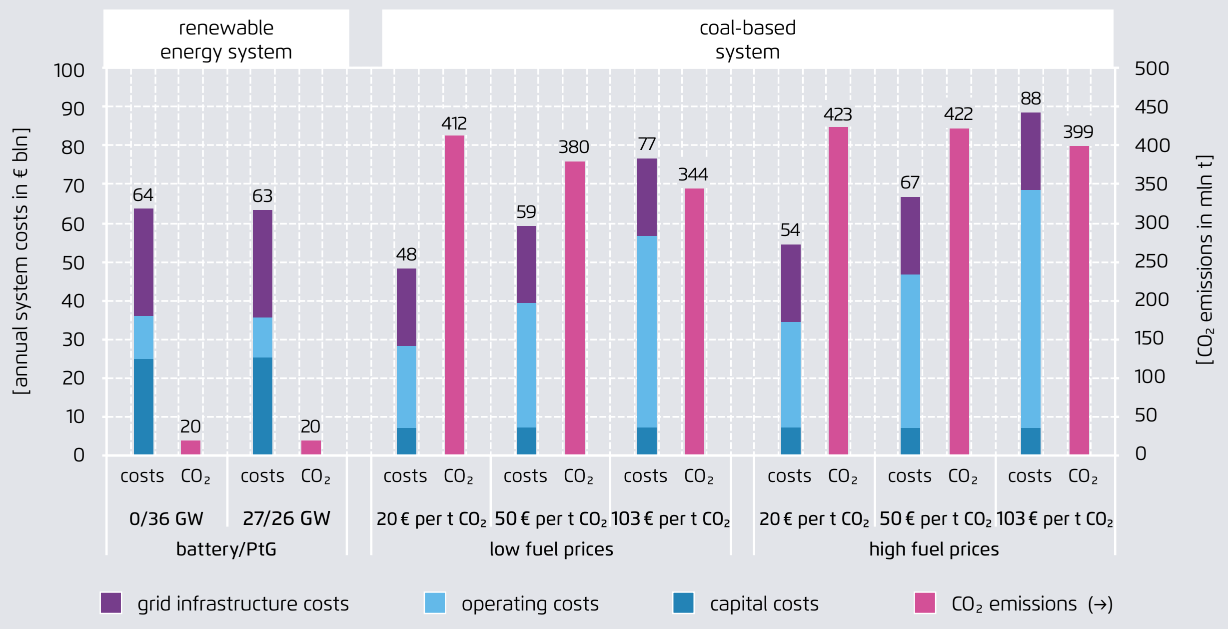
4.4. Comparison of electricity supply systems based on renewable energy and fossil fuels

A comparison of the system costs associated with the considered power system designs yields the following results:

1. The cost differences between the two renewable electricity systems are minimal, regardless of all other differences.
2. The system costs of the coal-based electricity system are only significantly (i. e. more than 5 percent) below those of the renewable electricity systems if fuel prices remain at a low level and CO_2 prices do not rise above 50 euros per tonne or, in the case of high fuel prices, remain significantly below 50 euros per tonne. This pattern also remains robust if the sensitivity analyses undertaken for the framework assumptions consider both fossil fuel and renewable power plants in combination with storage options. The only exception is the cost uncertainties relating to the expansion of grid infrastructure for renewable energy when CO_2 prices remain at approx. 50 euros per tonne or lower in the fossil-based electricity systems.
3. The total system costs of the natural gas-based electricity system are lower than those of the two renewable electricity systems when low fuel prices are assumed. The assumptions for CO_2 prices are

Total system costs of power system based on renewable energies compared to coal-based power system, 2050

Figure 4-10



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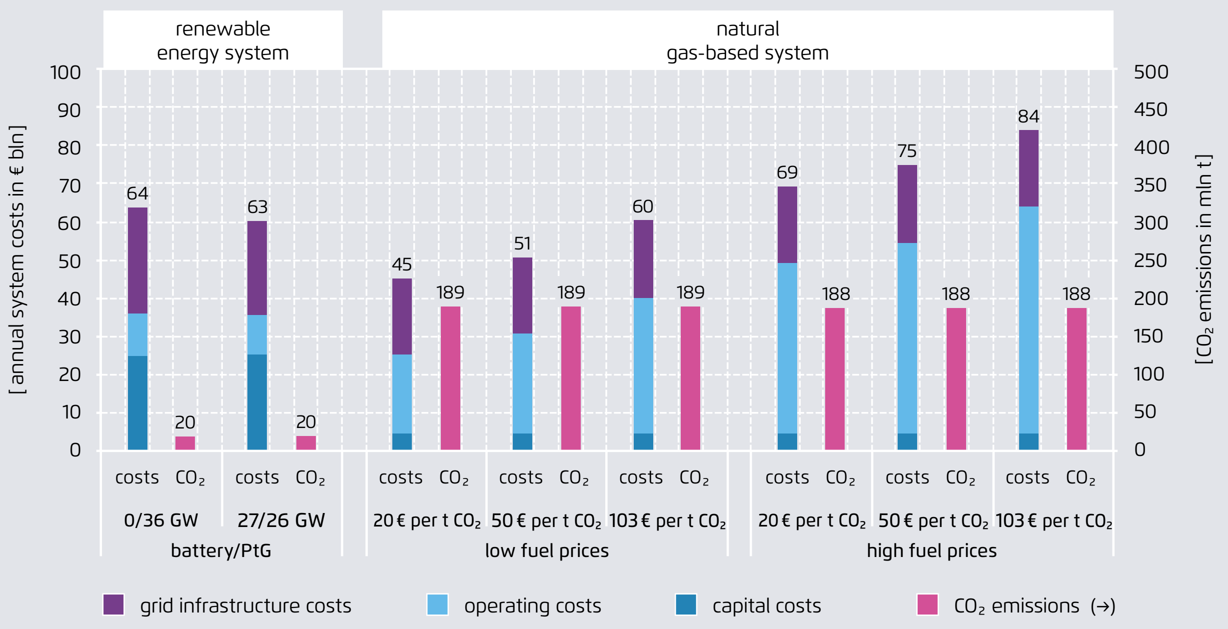
Total system costs of power system based on renewable energies compared to natural gas-based power system, 2050

Figure 4-11



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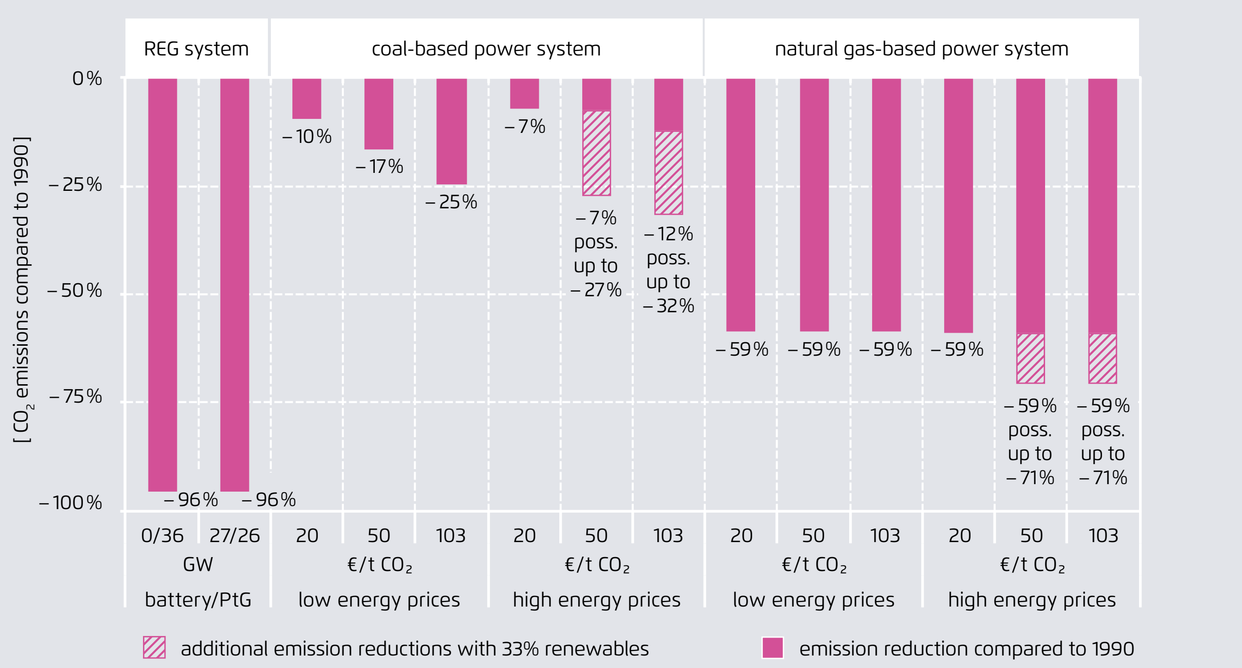
insignificant in such an environment. This result remains robust when the sensitivity analyses of the renewable electricity systems are incorporated, with the exception of the costs for infrastructure expansion, as long as the CO_2 costs do not substantially exceed 50 euros per tonne. It should be noted in this context that the hypothesis of largely unchanged grid infrastructure costs for a German electricity supply system based completely on natural gas is an extremely optimistic one.

The system costs should not, however, be considered independently of the targeted emission reductions (Figure 4-10 and Figure 4-11). In the final analysis, all scenarios based on a conventional coal-based mix fail to meet the emission reduction targets of the energy transition by a wide margin, even if there is some expansion in wind and solar electricity generation in the context of high fuel or CO_2 prices (Figure 4-12). However, in these cases, there are no significant advantages in the system costs for the coal-based electricity systems compared to the electricity systems based extensively on renewable energy.
A power system based completely on natural gas results in emission reductions of approx. 60 percent. If the natural gas-based power plant fleet is supplemented by a small share of wind and solar power plants in a market with high energy and CO_2 prices, emission reductions of approx. 70 percent could be achieved. However, in these cases, even when the various sensitivities in renewable systems are taken into account, there are no significant cost advantages in comparison to a system with a 95 percent share of renewables (a system that also allows emission reductions of over 95 percent to be achieved).

The interrelationship between system costs and targeted emission reductions can be considered by calculating the "system costs for emission reductions". This figure is determined based on the sum of CO_2 prices and the system cost differences between renewable systems while also considering associated CO_2 emission levels.

Vergleich der CO_2-Minderungen regenerativ und fossil dominierter Stromsysteme, 2050 — Abbildung 4-12



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The comparison between the two renewable systems and the coal-based electricity system results in system costs for emission reductions of approx. 60 euros per tonne of CO_2 when low fuel prices are assumed and approx. 40 euros per tonne of CO_2 when high fuel prices are assumed, i. e. these costs are comparatively attractive and in any case reasonable.

Compared to a natural gas-based electricity system that is highly sensitive to the fuel price, the difference costs amount to approx. 125 euros per tonne of CO_2 when low natural gas prices are assumed and are thus very high. For the scenarios with high fuel prices, the difference costs are negative at approx. –15 euros per tonne of CO_2.

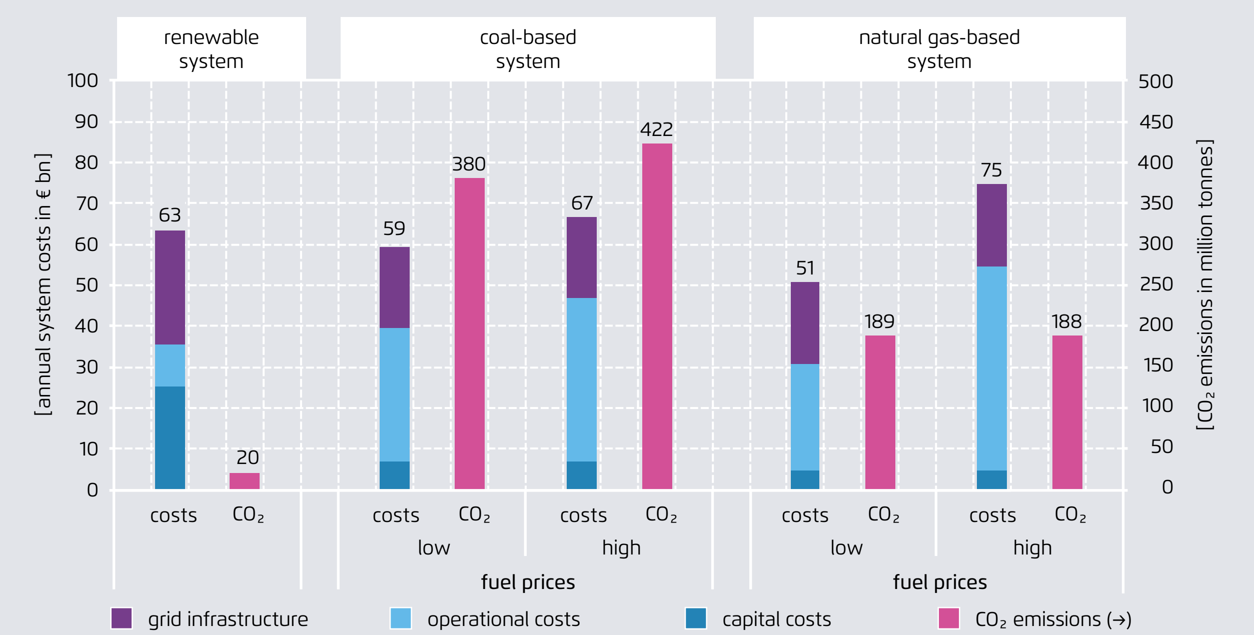
This basic pattern of system costs for emission reductions does not change when the various sensitivity analyses are applied.

Figure 4-13 shows an overview of the emission reduction and system cost assessments for the different designs of the German electricity supply system, assuming a CO_2 price of 50 euros per tonne.

This figure shows that the costs of electricity supply systems with a 95 percent renewable energy share do not significantly differ from those of fossil-based systems with lignite, hard coal and natural gas power plants. The sensitivity of their system costs diminishes with a view to fuel price developments. The emission reductions that can be achieved with a conventional fossil-based power generation mix – 17 or 7 percent – remain far behind the *Energiewende* targets and the emission reduction achievable with systems based on renewable energy.

An electricity system that is based almost completely on natural gas can achieve significantly larger emissions reductions of approx. 60 percent, although this remains far behind the *Energiewende* targets. The system costs, however, face substantial risks in terms of fuel price developments.

Comparison of total system costs of predominantly renewable, coal and natural gas-based power systems with CO_2 prices of €50, 2050 Figure 4-13



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5. Conclusions

The developments initiated in Germany's electricity supply system over the next few years will have substantial consequences up to 2050. The path that is taken will not only determine the emission reductions achievable by mid-century, but also the future system costs of the power system.

This study compared two different scenarios for an electricity system with a 95 percent share of renewables as well as two electricity systems based on fossil fuels. This comparison allows us to estimate relative system costs and evaluate the results from the perspective of climate policy.

The following conclusions can be drawn for the situation at mid-century, considering a range of different framework conditions that were assessed with sensitivity analyses:

1. Very ambitious emission reduction targets for the electricity sector – i. e. a far-reaching decarbonization of the electricity system – are possible in the context of Germany's Energy Concept only if the system is based extensively on renewable energy.
2. There are various options for the design of renewables-based system that enables reduction targets to be met. A fully functioning system that ensures security of supply can be realised through various combinations of renewable energy, flexibility options and grid infrastructure.
3. The costs of an electricity system based on renewables will be primarily attributable to capital costs, which will create challenges in terms of financing, yet such a system will have low sensitivity to fluctuating fuel and CO_2 prices, which are difficult to estimate over long time frames.
4. Compared to different designs of fossil-based electricity systems, the systems based extensively on renewable energy lead to substantially lower CO_2 emissions and have comparable or advantageous costs when high fuel prices and CO_2 prices of 50 euros or more per tonne are assumed. Only in the case of low energy and CO_2 prices or low energy prices and an electricity system based completely on natural gas are the system costs of fossil-based electricity systems substantially below those of electricity systems based on renewable energy – without, however, it being possible to achieve comparable emission reductions.
5. If the different emission reductions are incorporated, emission reduction costs of a maximum of 60 euros per tonne of CO_2 arise for electricity systems based extensively on renewable energy with one exception (an electricity system based exclusively on natural gas with permanently low natural gas prices). Compared to a natural gas-based electricity system with high fuel costs, the emission reduction costs for renewable electricity systems are especially attractive, at -15 euros per tonne of CO_2. Compared to a purely natural gas-based system and (permanently) low natural gas prices, the emission reduction costs reach a critical level, amounting to approx. 125 euros per tonne of CO_2.
6. With a view to the achievable emission reductions, the system costs and the reasonableness of the reduction costs, electricity systems based extensively on renewable energy are very robust in most of the circumstances considered.
7. These results do not change when it is considered that the definition of system boundaries tends to be conservative for electricity systems based on renewable energy (cross-sector or cross-border effects are not considered; the analysis of flexibility options is limited to storage; grid infrastructure costs are conservatively estimated, etc.) and that sensitivity analyses have been conducted to reduce the projection uncertainties remaining in several areas.

As a secondary result of the analyses, it can be concluded that emission reductions in fossil-based electricity systems always occur as a product of interaction between the high sunk costs of mines and conventional plants, energy prices and achievable CO_2 prices. To the extent that prices on international commodity markets are not amenable to policy intervention, robust emission reduction strategies – i. e. strategies that remain effective in the face of fuel price volatility – can only be achieved through CO_2 pricing and the guided management of the power plant fleet.

Considering current and future trends in the development of renewable energy and associated flexibility options, the long-term and far-reaching transformation of Germany's power system to one based on renewable energy is possible with a view to achieving climate policy goals and would also be efficient from a system cost perspective. Furthermore, such a transformation would represent an economically robust strategy for insuring against volatile commodity price trends.

6. References

50Hertz Transmission; Amprion; TenneT TSO; TransnetBW (2016). Netzentwicklungsplan Strom 2025, Version 2015. Zweiter Entwurf der Übertragungsnetzbetreiber, Berlin, Dortmund, Bayreuth, Stuttgart. www.netzentwicklungsplan.de/sites/default/files/paragraphs-files/NEP_2025_2_Entwurf_Teil1.pdf, retrieved on 12.01.2017.

50Hertz Transmission (50Hertz) (2016). Energiewende Outlook 2035. Entwicklungspfade der Energiewende und deren Folgen, Berlin. www.50hertz.com/Portals/3/Content/Dokumente/Netzausbau/Wof%C3%BCr%20Netzausbau/EWO%202035/50Hertz_Energiewende_Outlook_2035.pdf, retrieved on 25.09.2016.

American Physical Society (APS) (2011). Direct Air Capture of CO_2 with Chemicals. A Technology Assessment for the APS Panel on Public Affairs, College Park, MD. www.aps.org/policy/reports/assessments/upload/dac2011.pdf, retrieved on 25.09.2016.

Bundesministerium für Wirtschaft und Energie (2015). Die Energie der Zukunft. Vierter Monitoring-Bericht zur Energiewende, Berlin. www.bmwi.de/BMWi/Redaktion/PDF/V/vierter-monitoring-bericht-energie-der-zukunft,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf, retrieved on 12.01.2017.

Bundesnetzagentur (BNetzA); Bundeskartellamt (BKartA) (2016). Monitoringbericht 2015. Monitoringbericht gemäß § 63 Abs. 3 i. V. m. § 35 EnWG und § 48 Abs. 3 i. V. m. § 53 Abs. 3 GWB, Bonn.

Consentec; Fraunhofer-Institut für Windenergie und Energiesystemtechnik (Fraunhofer IWES) (2013). Kostenoptimaler Ausbau der Erneuerbaren Energien in Deutschland. Ein Vergleich möglicher Strategien für den Ausbau von Wind- und Solarenergie in Deutschland bis 2033. Study on behalf of Agora Energiewende, Berlin. www.agora-energiewende.de/fileadmin/downloads/presse/Pk_Optimierungsstudie/Agora_Studie_Kostenoptimaler_Ausbau_der_EE_Web_optimiert.pdf, retrieved on 25.09.2016.

Cressey, D. (2015). Firms that suck carbon from air go commercial. Nature 526, S. 306–307. www.nature.com/polopoly_fs/1.18551!/menu/main/topColumns/topLeftColumn/pdf/526306a.pdf, retrieved on 25.09.2016.

Department of Energy & Climate Change (DECC) (2015). Updated short-term traded carbon values used for UK public policy appraisal, London. www.gov.uk/government/uploads/system/uploads/attachment_data/file/477540/Updated_short-term_traded_carbon_values_used_for_UK_policy_appraisal__2015_.pdf, retrieved on 25.09.2016.

Deutsche Energie-Agentur (2012). dena-Verteilnetzstudie. Ausbau- und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030, Berlin. shop.dena.de/fileadmin/denashop/media/Downloads_Dateien/esd/9100_dena-Verteilnetzstudie_Abschlussbericht.pdf, retrieved on 25.09.2016.

E-Bridge Consulting; Institut für elektrische Anlagen und Energiewirtschaft; Offis (2014). Moderne Verteilernetze für Deutschland. Study on behalf of Bundesministerium für Wirtschaft und Energie (BMWi), Bonn, Aachen, Oldenburg. www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/Studien/verteilernetzstudie,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf, retrieved on 12.01.2017.

E-Bridge Consulting (E-Bridge); Büro für Energiewirtschaft und technische Planung (BET); Institut für elektrische Anlagen und Energiewirtschaft (IEAW) (2011). Abschätzung des Ausbaubedarfs in deutschen Verteilungsnetzen aufgrund von Photovoltaik- und Windeinspeisungen bis 2020. Study on behalf of BDEW, Bonn, Aachen.

Eichman, J.; Townsend, A. & Melaina, M. (2016). Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets. Golden, CO: National Renewable Energy Laboratory. www.nrel.gov/docs/fy16osti/65856.pdf, retrieved on 25.09.2016.

Elsner, P. & Sauer, D. U. (2015). Energiespeicher. Technologiesteckbrief zur Analyse "Flexibilitätskonzepte für die Stromversorgung 2050" (Schriftenreihe Energiesysteme der Zukunft), München, Halle (Saale), Mainz.

Energy Information Administration (EIA) (2016a). Cost and Performance Characteristics of New Generating Technologies in the Anual Energy Outlook 2016, Washington, DC. www.eia.gov/forecasts/aeo/assumptions/pdf/table_8.2.pdf, retrieved on 25.09.2016.

Energy Information Administration (EIA) (2016b). Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016, Washington, DC. www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf, retrieved on 25.09.2016.

European Commission (2011a). Energy Roadmap 2050. Impact Assessment - Part 1. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions (SEC(2011)1565-2), Brussels. ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part1.pdf, retrieved on 25.09.2016.

European Commission (2011b). Energy Roadmap 2050. Impact Assessment – Part 2. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions (SEC(2011)1565), Brussels. ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part2.pdf, retrieved on 25.09.2016.

Feldman, D.; Margolis, R. & Denholm, P. (2016). Exploring the Potential Competitiveness of Utility-Scale Photovoltaics plus Batteries with Concentrating Solar Power, 2015–2030. Golden, CO: National Renewable Energy Laboratory. www.nrel.gov/docs/fy16osti/66592.pdf, retrieved on 25.09.2016.

Forschungsstelle für Energienetze und Energiespeicher (FENES); Institut für elektrische Anlagen und Energiewirtschaft (IEAW); ef.Ruhr; Institut für Stromrichtertechnik und Elektrische Antriebe (ISEA) (2014). Stromspeicher in der Energiewende. Untersuchung zum Bedarf an neuen Stromspeichern in Deutschland für den Erzeugungsausgleich, Systemdienstleistungen und im Verteilnetz. Study on behalf of Agora Energiewende, Berlin.

Fraunhofer-Institut für System- und Innovationsforschung (Fraunhofer ISI) (2014). Analyse der Netzausbaukosten und der Kostenverteilungswirkung. Untersuchung im Rahmen des Projekts "Wirkungen des Ausbaus erneuerbarer Energien (ImpRES)", gefördert durch das Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Karlsruhe. www.impres-projekt.de/impres-wAssets/docs/2014_08_03_Netzausbaukosten-ImpRES_final.pdf, retrieved on 25.09.2016.

Fraunhofer-Institut für Windenergie und Energiesystemtechnik (Fraunhofer IWES) (2015). Wie hoch ist der Stromverbrauch in der Energiewende? Energiepolitische Zielszenarien 2050 – Rückwirkungen auf den Ausbaubedarf von Windenergie und Photovoltaik. Study on behalf of Agora Energiewende, Berlin. www.agora-energiewende.de/fileadmin/Projekte/2015/Stromverbrauch_in_der_Energiewende/086_IWES_Szenarienvergl_dt_WEB.pdf, retrieved in October 2015.

Fraunhofer-Institute for Solar Energy Systems (Fraunhofer ISE) (2015). Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. Study on behalf of Agora Energiewende, Berlin.

Frontier Economics (Frontier); Consentec (2014). Folgenabschätzung Kapazitätsmechanismen (Impact Assessment). Report on behalf of Bundesministerium für Wirtschaft und Energie, Köln, Aachen.

Görner, K. & Sauer, D. U. (2016). Konventionelle Kraftwerke. Technologiesteckbrief zur Analyse "Flexibilitätskonzepte für die Stromversorgung 2050" (Schriftenreihe Energiesysteme der Zukunft), München, Halle (Saale), Mainz. www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Materialien/ESYS_Technologiesteckbrief_Konventionelle_Kraftwerke.pdf, retrieved on 25.09.2016.

IHS Markit (IHS) (2016). The IHS European Power Capital Costs Index (EPCCI), London. www.ihs.com/Info/cera/ihsindexes/, retrieved on 25.09.2016.

International Energy Agency (IEA) (2016). World Energy Outlook 2016, Paris.

National Renewable Energy Laboratory (2012). Renewable Electricity Futures Study. Volume 2: Renewable Electricity Generation and Storage Technologies (NREL/TP-6A20-52409), Golden, CO. www.nrel.gov/docs/fy12osti/52409-2.pdf, retrieved on 25.09.2016.

Öko-Institut (2014). Prüfung der klimapolitischen Konsistenz und der Kosten von Methanisierungsstrategien, Berlin. www.oeko.de/oekodoc/2005/2014-021-de.pdf, retrieved on 25.09.2016.

Öko-Institut; Fraunhofer-Institut für System- und Innovationsforschung (Fraunhofer ISI) (2015). Klimaschutzszenario 2050. 2. Runde. Study on behalf of Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, Berlin, Karlsruhe.

P3 Energy; Institut für Hochspannungstechnik (IFHT) (2012). Szenarien für eine langfristi ge Netzentwicklung. Study on behalf of Bundesministerium für Wirtschaft und Technologie, Aachen.

Prognos; Energiewirtschaftliches Institut an der Universität zu Köln (EWI); Gesellschaft für wirtschaftliche Strukturforschung (GWS) (2014). Entwicklung der Energiemärkte – Energiereferenzprognose. Projekt Nr. 57/12, Study on behalf of Bundesministerium für Wirtschaft und Technologie, Basel, Köln, Osnabrück.

PTV Group (PTV); TCI Röhling – Transport Consulting International (TCI); Mann, Hans-Ulrich (2016). Methodenhandbuch zum Bundesverkehrswegeplan 2030. Bericht für das Bundesministerium für Verkehr und digitale Infrastruktur (BMVI), Karlsruhe, Berlin, Waldkirch, München. www.bmvi.de/SharedDocs/DE/Anlage/VerkehrUndMobilitaet/BVWP/bvwp-2030-methodenhandbuch.pdf?__blob=publicationFile, retrieved on 25.09.2016.

Quaschning, V. (2016). Sektorkopplung durch die Energiewende. Anforderungen an den Ausbau erneuerbarer Energien zum Erreichen der Pariser Klimaschutzziele unter Berücksichtigung der Sektorkopplung. Berlin: Hochschule für Technik und Wirtschaft Berlin (HTW). pvspeicher.htw-berlin.de/wp-content/uploads/2016/05/HTW-2016-Sektorkopplungsstudie.pdf, retrieved on 25.09.2016.

Rech, B. & Elsner, P. (2016). Photovoltaik. Technologiesteckbrief zur Analyse "Flexibilitätskonzepte für die Stromversorgung 2050" (Schriftenreihe Energiesysteme der Zukunft), München, Halle (Saale), Mainz, retrieved on 25.09.2016.

Research to Business Energy Consulting (r2b) (2014). Funktionsfähigkeit EOM & Impact-Analyse Kapazitätsmechanismen. Endbericht Leitstudie Strommarkt on behalf of Bundesministerium für Wirtschaft und Energie, Köln.

Umweltbundesamt (UBA) (2014b). Treibhausgas-neutrales Deutschland im Jahr 2050 (UBA Climate Change 07/2014), Dessau-Roßlau. www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/07_2014_climate_change_dt.pdf, retrieved on 25.09.2016.

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