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GERMANY'S ELECTRIC FUTURE

Coal phase-out 2035

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Foreword

The planet has a limit and it shows us this forcefully. With record temperatures, melting poles, acidified seas. With dying species. Not least of all, humans are affected: every year the emissions of coal-fired power plants in Germany cause several thousand premature deaths. Reason enough to respect the Earth's limits – also in the way in which we generate electricity. But this necessitates a serious and far-reaching change in the energy sector. Decision-makers in politics and the economy are still too timid to take the necessary steps. And yet time is running out for an accelerated phase-out of coal.

The present study by Öko-Institut and Prognos AG, which was carried out on behalf of WWF Germany, tackles this issue. With an approach that points the way ahead, the leading research institutes have calculated a robust phase-out path for coal-fired electricity in Germany based on the carbon budget.

The carbon budget takes the Paris Agreement as its yardstick: the Parties have agreed to limit global warming to well below two degrees Celsius. To achieve this, only a limited amount of CO_2 – a maximum of 890 gigatonnes worldwide – is allowed to enter the atmosphere. This means that the German electricity sector, which is responsible for approx. 40 percent of Germany's greenhouse gas emissions, can only emit four gigatonnes of CO_2.

The analyses build on this foundation. They show how Germany can make a fair contribution to global climate protection efforts without causing bottlenecks in the electricity supply. The pace of the coal phase-out is, however, decisive. There is no time left to postpone the problem. The time is also short for keeping structural breaks in regions to a minimum and for keeping the costs of energy transition low. The study further shows that efforts must not be limited to the coal phase-out – the focus also needs to be on the expansion of renewable energies and the power grids.

WWF wants to contribute to the design of Germany's future electricity system. The accelerated phase-out of coal is a prerequisite for an electric future that is based on renewable energies. WWF cannot, of course, provide all the answers on its own. The comprehensive calculations in this study can be used as a basis in the upcoming discussions and decisions for collectively getting the coal phase-out in Germany off the ground. WWF will not only accompany this process, it will also actively drive it on.

Christoph Heinrich
Executive Officer of Conservation, WWF Germany

Inhalt

Executive Summary

The German electricity sector is of paramount importance for both energy and climate policy. The electricity sector's share of emissions within total greenhouse gas emissions (taking into account non-CO_2 greenhouse gases and the emissions from fuel quantities tanked in Germany for international transport) currently amounts to approx. 37%. The electricity sector makes by far the largest single contribution to the release of greenhouse gases into the atmosphere. In terms of the total greenhouse gas reduction brought about to date, the electricity sector has made a disproportionately low contribution since 1990. With the largely stagnating contributions of the electricity sector to these emission reductions, the pressure is increasing for the sector to take greater action.

Given that German lignite and hard coal-fired power plants currently account for approx. 80% of the total CO_2 emissions of the electricity sector (48% from lignite and 33% from hard coal-fired electricity generation), progress can only be made in reducing the sector's CO_2 emissions if the phasing-out of coal-based electricity generation is made a high priority. The fact that the German coal-fired power plant fleet has very high shares of comparatively old (and refinanced) power plants that entered operation before 1990 and have particularly high emissions (48% of the generation capacity installed in lignite and 51% of the generation capacity installed in hard coal-fired power plants) is highly relevant in this context. The crucial question is, on the one hand, which paths are helpful and necessary for decreasing and phasing-out coal-based electricity generation and, on the other hand, which political strategies and policy instruments can trigger the developments needed. Coal-based electricity generation is highly relevant today, not only in terms of its significance for CO_2 emissions but also in terms of its important role in electricity supply (approx. 40% of net electricity generation and approx. 45% of dispatchable generation capacity in Germany). Lignite also has a partially high regional economic significance. This makes holistic strategies and implementation measures necessary.

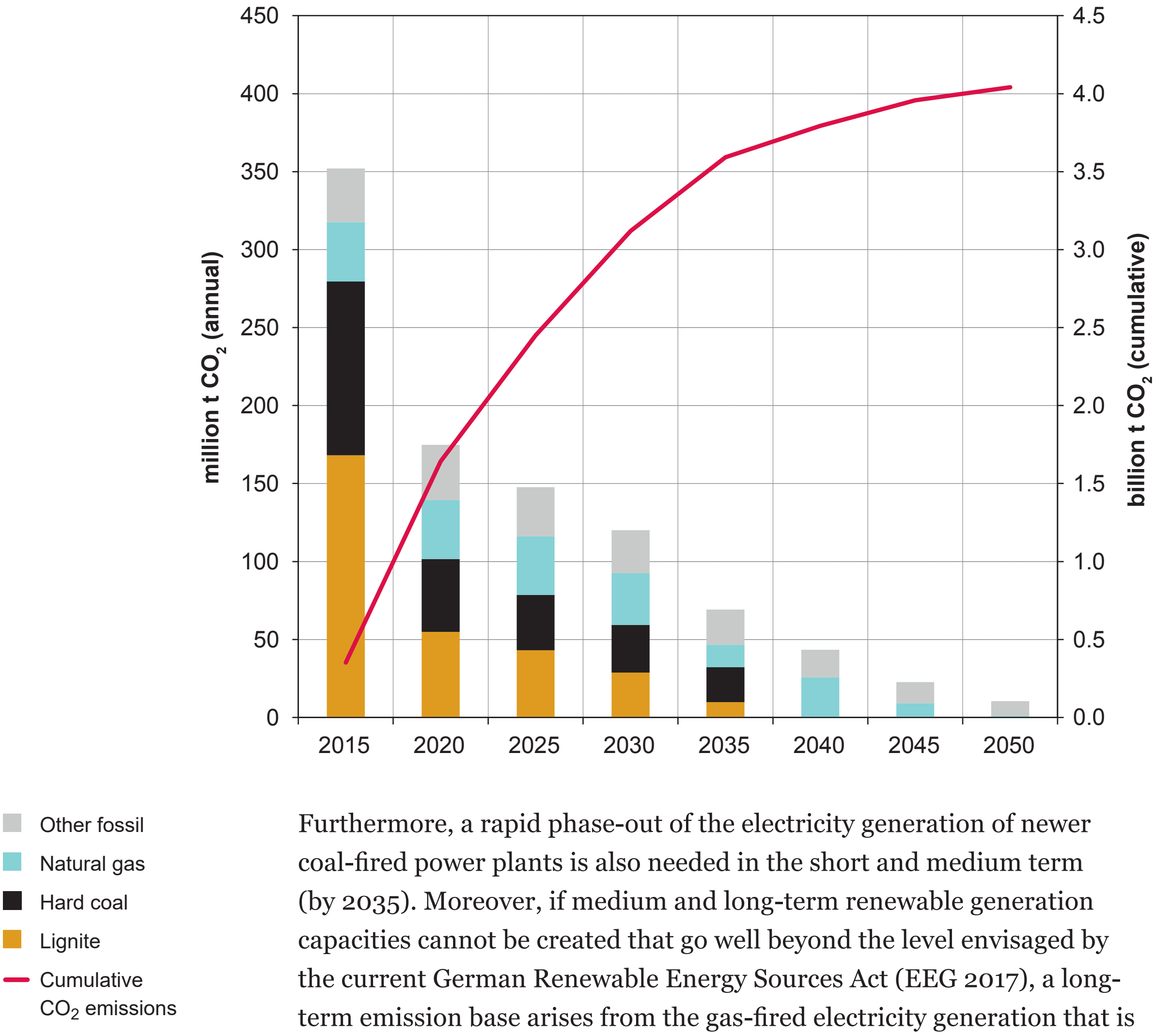
In view of phase-out paths for coal-based electricity generation, the 2015 Paris Agreement that came into force in 2016 has created a new framework of reference. The Paris Agreement's central aim is to limit the increase in global mean temperature to well below 2°C compared to pre-industrial levels. The Agreement also pursues efforts to limit the temperature increase even further to 1.5°C. The targeted limit is the central indicator for assessing the climate policy ambitions of individual states within the architecture of the Paris Agreement. It leads to a less rigid focus on emission reduction targets for specific time horizons or target years, and a stronger consideration of the emission budget concept, which seems more suitable with a view to the effects needed from the measures.

From analyses conducted on the requirements for adhering to the 2°C limit in global temperature increase, clear CO_2 emission budgets can be derived for both Germany and the German electricity sector based on transparent distribution concepts. The concept of emission budgets geared to a specific country (derived using a global per capita approach and without taking into account historical emissions) and a specific sector (derived using approximately proportional emission reductions in the different sectors) has proven to be a productive approach for identifying, on the level of smaller scopes of action, fair contributions to be made in order to meet the global targets. With an emissions budget for Germany of approx. 10 billion t CO_2 for the period of 2015 to 2050, the emissions budget for the German electricity sector amounts to between 4.0 and 4.2 billion t CO_2.

Analyses on the phasing-out of German coal-based electricity generation that consider the field of tension between technically feasible adaptation processes and regulatory boundaries for the necessary measures, clearly show that adhering to an emission budget of 4.0 to 4.2 billion t CO_2 for the period of 2015 to 2050 is possible in principle. For this to be achieved, significant emission reductions need to be implemented relatively quickly (Figure S-1).

Figure S-1: **Annual and cumulative CO_2 emissions in the Transformation Scenario for an accelerated phase-out of coal-based electricity generation in Germany, 2015–2050**

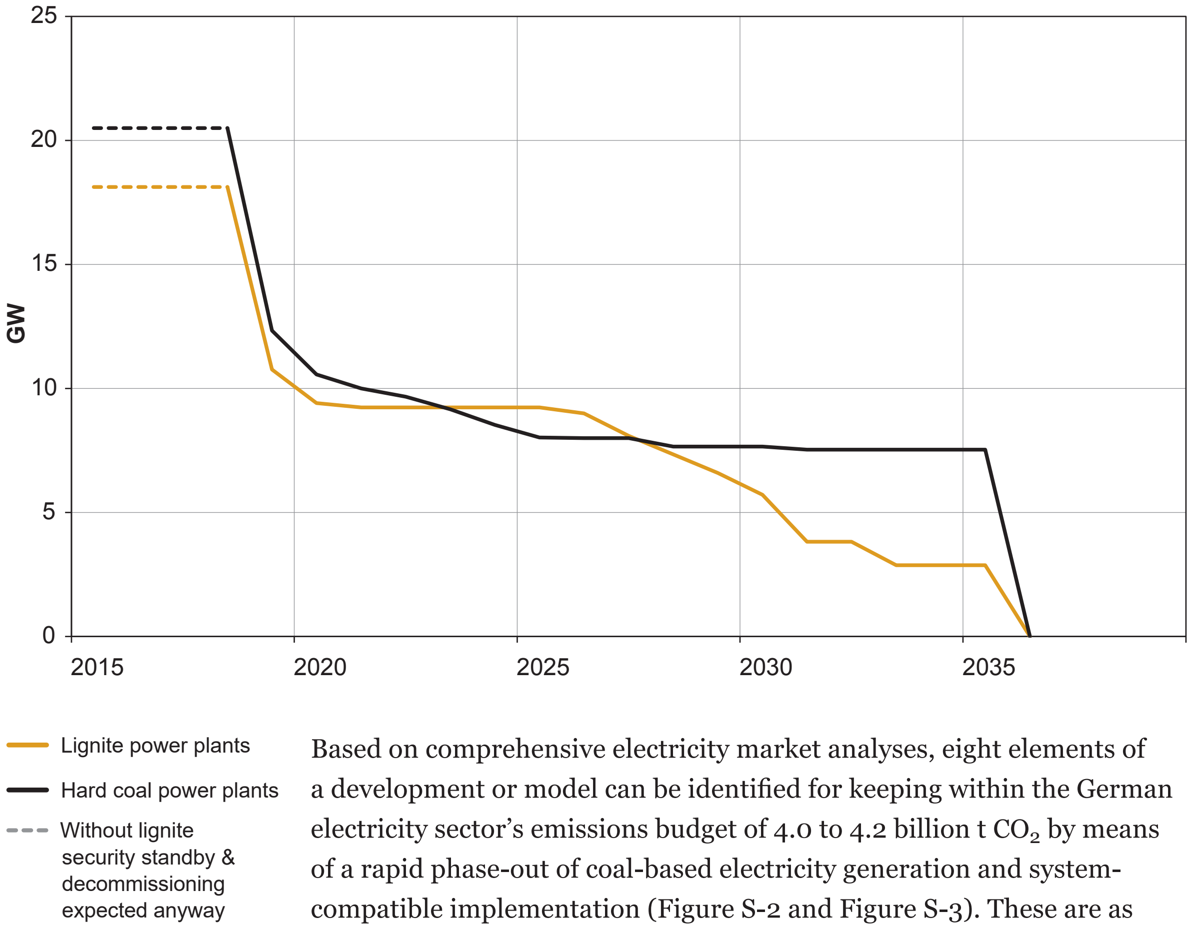
Source: Calculations by Öko-Institut and Prognos



Furthermore, a rapid phase-out of the electricity generation of newer coal-fired power plants is also needed in the short and medium term (by 2035). Moreover, if medium and long-term renewable generation capacities cannot be created that go well beyond the level envisaged by the current German Renewable Energy Sources Act (EEG 2017), a long-term emission base arises from the gas-fired electricity generation that is then needed to balance the reduction in coal-fired electricity generation; this emission base also contributes to the CO_2 emission budget being exceeded.

Figure S-2: **Reduction of lignite and hard coal-based generation capacities in the Transformation Scenario for an accelerated phase-out of coal-based electricity generation in Germany, 2015–2035**

Source: Calculations by Öko-Institut and Prognos



Based on comprehensive electricity market analyses, eight elements of a development or model can be identified for keeping within the German electricity sector's emissions budget of 4.0 to 4.2 billion t CO_2 by means of a rapid phase-out of coal-based electricity generation and system-compatible implementation (Figure S-2 and Figure S-3). These are as follows:

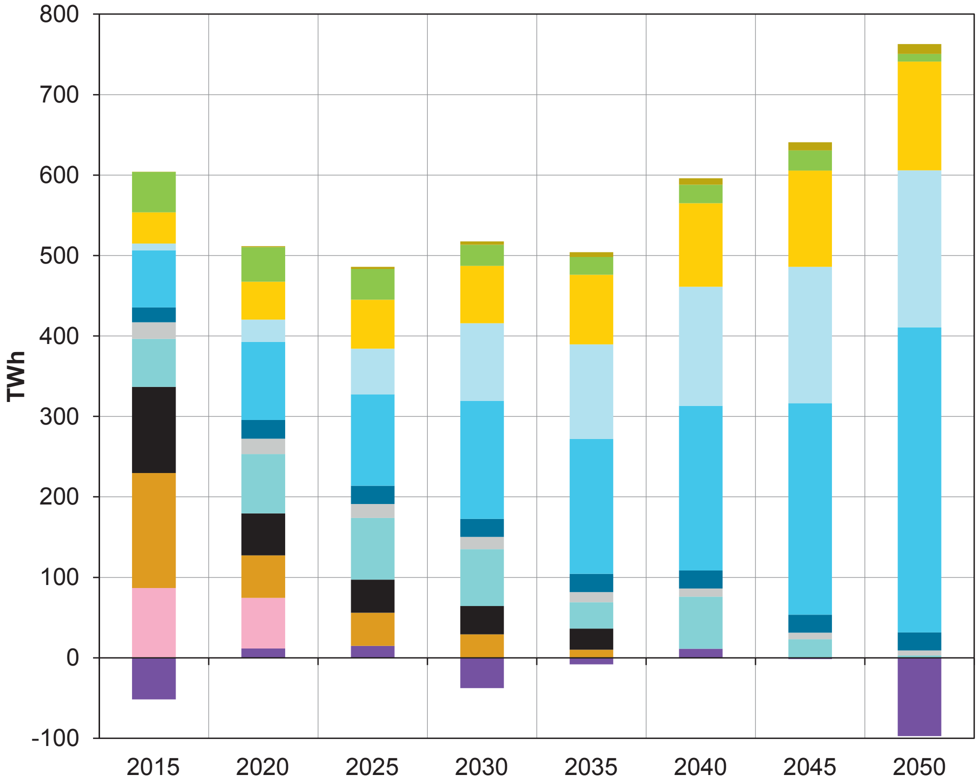
- The first key element is to accelerate the expansion of electricity generation based on renewable energies to the level originally envisaged by EEG 2014 and the 2030 Network Development Plan.

- The second element is to decommission in the short term coal-fired power plants that have been in operation for more than 30 years. The reduction of these capacities should start in 2019, given the high emission base of the coal-fired power plant fleet and the tight CO_2 emissions budget.

- The third element is to set the end of 2035 as the deadline for completing the phase-out of lignite and hard coal-fired electricity generation.

Figure S-3: **Electricity generation in the Transformation Scenario for an accelerated phase-out of coal-based electricity generation in Germany, 2015–2050**

Source: Calculations by Öko-Institut and Prognos



» The fourth element is to implement a mix of capacity and emission management to establish continuity in emission reductions, capacity reduction and electricity market effects and to facilitate the adaptation processes for companies and regions for the period of 2019 to 2035.

» The fifth element is the need to develop instruments which, on the one hand, reduce the high export surpluses of Germany from CO_2-intensive electricity generation and, on the other hand, strive to achieve a balanced decade average of electricity imports and exports (fossil-generated power) from 2020 onwards.

» The sixth element is the need to review, in the context of the rapid phase-out of coal-based power generation, the already implemented and planned instruments for ensuring system stability and security of supply.

» The seventh element concerns the regulatory framework for open-cast lignite mining. In view of the German electricity sector's CO_2 emission budget, which is compatible with the 2°C temperature limit, all lignite mining areas that have already received approval for lignite quantities to be mined should expect to be decommissioned sooner than envisaged. Approval procedures for expansions of existing open-cast mines should be stopped until the phase-out path for coal-based power generation in Germany has been reliably clarified and reasonable reductions have been shown with legal certainty. The associated consequences (financing of follow-up costs, etc.) have to be taken into consideration at an early stage.

» An eighth element is the need to conduct comprehensive analyses on the regional economic and social impacts of a rapid phase-out of coal-fired electricity generation and the creation of necessary compensation mechanisms (from the expansion of renewable energies, through location policy to infrastructure expansion).

Against this background, the main elements of instruments needed for phasing-out coal-fired electricity generation in Germany are as follows:

1. The date set for completing the phase-out of coal-fired electricity generation in Germany by 2035 needs to be laid down in a regulation. With a view to the age structures of the affected power plants, this means, with some exceptions, a minimum plant operating life of 20 years.

2. Limiting the operating life of coal-fired power plants to a maximum of 30 years can be implemented via legal regulation or by contractual arrangements. In both cases, this can, at least in principle, be combined with compensation payments; however, it should be pointed out that this approach deviates from the polluter pays principle and should therefore be considered a less suitable option from this perspective.

3. Optimizing power plant operation from the 21st to the 30th operating year (after commercial operation commenced) – which results in the yearly emissions of the power plant being limited to a maximum of 3.35 t CO_2 per kilowatt of net output – can be implemented both via legal regulation (e.g. following the model of the British emissions performance standard on which the modelling is based) and via pricing mechanisms (minimum price in the EU Emissions Trading System, selective pricing according to the climate levy model) or via compensation payments. Due to its deviation from the polluter pays principle, the latter approach should also be regarded as less suitable.

4. Finally, the dismantling and renaturation of open-cast mining areas should be financially secured with the strict participation of the polluters. Expansions of existing open-cast mines should not be pursued further; legally secure approaches to reasonable and necessary reductions in the scope of existing open-cast mining must be developed relatively quickly.

From an overall perspective, therefore, a broad spectrum of options is available for developing instruments to phase out German coal-fired electricity generation by 2035. The options can be implemented within the context of very different preferences and (European) policy framework conditions.

In addition to the implementation of a rapid phase-out of coal-fired electricity generation in Germany, in narrow climate and energy policy terms, further measures have to be taken to broaden integration of the coal phase-out (social and regional economic adaptation strategies for lignite mining areas, incorporation in the electricity market design of the future, infrastructural aspects). These were not included in the present study; they cannot, however, be meaningfully conceived and implemented without specification of the phase-out path for coal-fired electricity generation.

1 Introduction

In recent years Germany has set very far-reaching long-term targets in climate and energy policy, and has taken the first steps in the development of implementation strategies by reaching an agreement on the German Energy Concept in 2010 and 2011 and adopting the 2050 Climate Action Plan in 2016. The time frame of these measures extends to mid-century.

Very far-reaching strategies for the worldwide reduction of greenhouse gas emissions, which aim to decarbonize the energy system in the final analysis, have gained considerable relevance since the Paris Agreement was adopted in 2015 (UNFCCC 2015). Since this internationally binding agreement came into force in 2016, far-reaching decarbonization strategies have been on the global agenda. Although the overwhelming majority of countries in the world have committed to climate protection activities under this agreement for the first time, highly industrialized countries like Germany continue to have a special responsibility. This responsibility is derived from their historically comparatively large contributions to the climate change that has already occurred and that is expected to occur. Germany has clearly acknowledged this responsibility in its climate protection and energy policy. For several legislature periods and under several different German governments, a pioneering role for Germany has been explicitly pursued, with the aim of bringing about a particularly rapid decarbonization of the energy system and very ambitious greenhouse gas emission reductions in the non-energy sectors.

This means that the medium and long-term conversion of energy supply to low and zero-emission technologies is on the energy policy agenda, which in Germany is to be predominantly achieved by the transition of its energy supply to one based on renewable energies. Robust strategies for designing a transformation path can be designed that are as effective, widely accepted, ecologically friendly and cost-efficient as possible. Alongside the expansion of the use of renewable energies in power generation and of complementary and flexibility options (demand flexibility, grids, storage, etc.), the actively shaped phase-out of fossil-based and particularly CO_2-intensive (coal-fired) electricity generation constitutes a second essential pillar of the transformation process. This process needs, in turn, to be broadly embedded in a portfolio of strategies and instruments of regional and structural policy.

The UNFCCC not only requires the participating countries to elaborate Nationally Determined Contributions (NDCs) but also to assess, at regular intervals, these plans in their entirety against the goal of limiting the increase in the global average temperature to (significantly) below 2°C compared to pre-industrial levels (and also to limit the global temperature increase to a maximum of 1.5°C) and to adapt the ambition level of the plans accordingly. Based on the need to go through this assessment cycle on a regular basis and to raise the ambition level of the nationally determined contributions, the question arises, firstly, of how to identify a fair share for Germany and, more specifically, for the German electricity sector to stay within the 2°C limit. The second question is what this means for the expansion of renewable electricity generation and the phase-out of coal-fired electricity generation, which is especially relevant to the emissions of the German electricity sector.

In this first report of the project "Germany's electric future", analyses are provided on the reasoning for and design of a phase-out path for fossil-fired electricity generation. Possible designs of Germany's future electricity system based extensively on renewable energies, the implications of these designs and corresponding energy and climate policy strategies are considered in the following analyses.

2 Methodological approach

The analyses of the developments of a robust and targeted phase-out path for coal-fired electricity generation in Germany progress through the following six steps:

1. The first step (chapter 3) analyzes the historical development of the German electricity sector in terms of demand, power generation and exchange structures and CO_2 emissions as well as the age structure of the lignite and hard coal power plant fleets.

2. In a second step (Chapter 4), the connections between cumulative CO_2 emissions and the increase in global average temperature are reviewed based on the analyses of the Intergovernmental Panel on Climate Change (IPCC 2013, 2014). From this, an approach for calculating a fair share for Germany and the German electricity sector of the global emission budget up to 2050 is derived.

3. In the third step (chapter 5), framework conditions are defined for the modelling, based on which robust policy strategies and implementation instruments can be derived for actively designing the phase-out process for coal-fired electricity generation in Germany.

4. The fourth step (chapter 6) analyzes the scope for solutions regarding the phase-out paths for coal in Germany's electricity sector. This scope is derived from the technical limits of short and medium-term adaptation processes in Germany's electricity system and from the range of possible intervention strategies. This analysis is undertaken using a combination of electricity market models of both Prognos and Öko-Institut (PowerFlex). The power plant fleets derived from the framework conditions and the expansion paths for power generation based on renewable energies constitute the two main variables:

   » The Prognos electricity market model is used for Europe-wide modelling of the corresponding framework conditions and to calculate the cross-border electricity flows, taking into account the market environments.

- Based on these electricity exchange structures calculated on an hourly basis, the effects on the German electricity system are modelled using Öko-Institut's PowerFlex model, which enables the data to be adapted to the emission structures and levels of the German greenhouse gas inventories and projection reports and thus also to the electricity quantities on which basis Germany would meet its emission reduction targets.

The following indicators are determined and discussed based on the results of this integrated modelling approach:

- the firm capacities on the supply and demand side needed for electricity supply and in order to guarantee security of supply[1];
- the structures of power generation and cross-border electricity flows;
- the annual CO_2 emissions;
- the cumulative CO_2 emissions for 2015 to 2050;
- the effects on the wholesale prices of the electricity exchanges.

5. Based on the findings of the fourth step, the structures of a targeted phase-out of coal are determined in a fifth step (chapter 7). This does not exceed the calculated emission budget and maintains a focus on the effects arising from the scope of electricity prices and security of supply.

   - The modelling approach and the instruments are the same as for the fourth step of the analysis.
   - Alongside the above-mentioned indicators, the consequences for lignite demand are determined and assessed for each of the mining districts in Germany.

1 Within the scope of the analyses presented, it was not possible to conduct a comprehensive assessment of security of supply. Rather, a first approximate analysis is undertaken that is geared to keeping within a total quantity of available firm capacity (approximate assessment of security of supply).

6. From the numerical model analyses, the consequences for long-term and – with a view to the development of the instruments – relatively flexible strategies for designing a phase-out path for coal are derived in a sixth step (chapter 8.1).

7. In a final seventh step, the different instrument options for the strategic implementation of a phase-out path for coal-fired electricity generation in Germany is discussed (chapter 8.2), also with regard to the EU Emissions Trading System (chapter 8.3).

This methodological approach enables the comprehensive classification and assessment of phase-out paths for coal in Germany's electricity sector in the context of a climate policy geared to a fair division of efforts to stay below the 2°C limit for the increase in global average temperature.

3 Historical development of Germany's electricity sector since 1990

The German electricity system has had relatively constant consumption levels since 2005. After the relatively large decline in gross electricity consumption from 1990 to 1992 that resulted from Germany's reunification, there followed a fifteen-year phase of relatively steady and significant (+17 %) increases in electricity demand. Since then, gross electricity consumption in Germany has declined only slightly (-2 %), but is currently[2] still substantially above the level at the turn of the millennium.

Table 3-1: Electricity consumption in Germany, 1990–2015

Source: German Working Group on Energy Balances (AGEB), German Federal Ministry for Economic Affairs and Energy, calculations by Öko-Institut

		1990	1995	2000	2005	2010	2015
		TWh					
Households		117	127	131	141	142	132
Tertiary		116	124	140	132	147	149
Industry		208	191	208	229	222	228
Transport		14	16	16	16	17	12
Energy industry (w/o power plants)		26	18	16	17	14	13*
Grid losses		23	23	24	29	24	25*
Pumped elec. consumption		5	6	6	10	9	8*
Own consumption of power plants		41	38	38	39	37	37*
Gross elec. consumption		**551**	**543**	**578**	**612**	**610**	**604***
For info purposes:	Imports	32	40	45	53	42	33
	Exports	31	35	42	62	60	85
	Net imports	1	5	3	-8	-18	-52

In the last 25 years the drivers of electricity consumption were, in approximately equal measure, households, industry and the tertiary sector. Correspondingly, the structures of electricity consumption in Germany have hardly changed in the last two decades (Table 3-1):

2 Insofar as the analyses presented here are based on data for 2015, it should be noted that all data (regarding energy and emissions) is provisional for this year and can be the subject to revision before the final energy balances are made available.

- The share of manufacturing industry and the mining of non-energy raw materials amounted to approx. 38% of total electricity consumption in 2015. From 1995 to 2015 the shares were between 24% and 38.5%. In 1990 – the year of Germany's reunification – the share of industry in total electricity consumption amounted to approx. 38%.

- The second largest source of electricity demand is the tertiary sector, which had an approx. 25% share in 2015 and a share ranging from 21.5% to 25% from 1995 to 2015. In 1990, the share of the tertiary sector was still 21%.

- Households currently account for a slightly smaller share (22%) of total gross electricity consumption in Germany. From 1995 to 2015, this share remained within the range of 22% and 24.5%; in 1990 it amounted to 21%.

- The transport sector has the smallest share in Germany's final electricity consumption, at approx. 2% in 2015; from 1995 to 2015 the share ranged between 2% and 3%.

- The energy industry without the electricity sector (refineries, lignite collieries, hard coal pits, natural gas and petroleum production, etc.) had an approx. 2% share of total power consumption in 2015. It had a significantly higher share in 1995 and 1990, at 3% and 5% respectively, reflecting how the production and processing of fossil fuels has been declining in Germany.

- Electricity consumption outside of the electricity supply system currently accounts for approx. 12% of gross electricity consumption in Germany, of which approx. 4 percentage points are attributed to grid losses, approx. 1% to the electricity consumption of the pumped-storage power plants and approx. 6% to the consumption by the power plants themselves (for pumps, flue gas purification plants, etc.). The shares have remained relatively constant over time; only the power plants' own consumption has declined slightly since 1995 (approx. 7%) and 1990 (7.5%) as a result of the decrease in the production share of power plants with relatively high own consumption (mainly coal-fired and nuclear power plants).

- Lastly, it should be noted that the share of electricity exports has increased substantially. After relatively balanced cross-border trade in electricity in the first decade of the 21st century, Germany's power exports have increased significantly, peaking at 52 TWh in 2015, which corresponds to an approx. 9% share of gross domestic electricity consumption. The development of net exports results in part from a slight decline in electricity imports over time and in part from the huge growth in electricity exports. The increase in Germany's electricity exports is attributable to the low prices on the wholesale market compared to the electricity markets of neighbouring countries: these low prices are justified by the low prices of hard coal and emission allowances and by the expansion of electricity generation based on renewable energies.

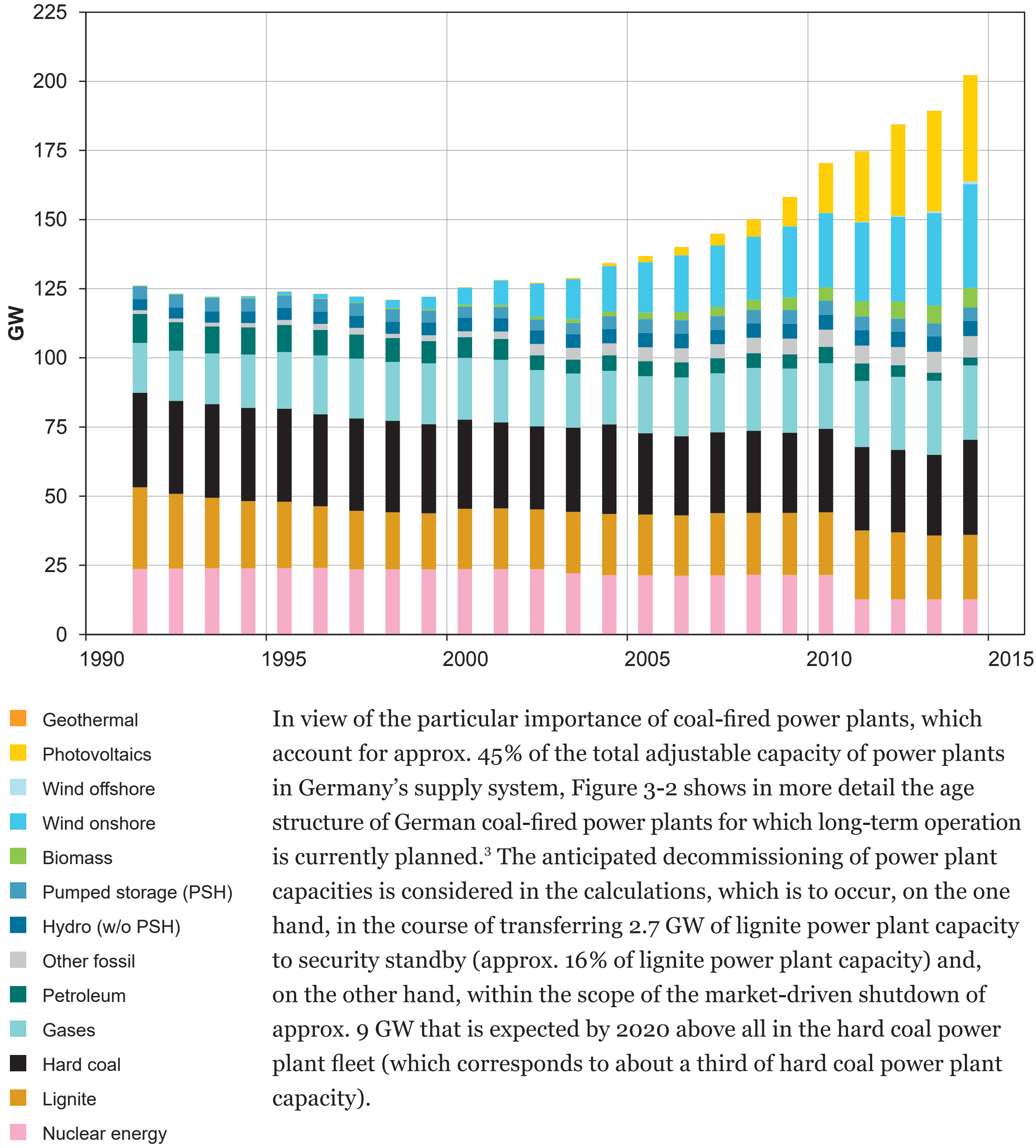
Germany's electricity demand and electricity exports are met by a power plant fleet that has changed significantly in the last 25 years, especially in the last 15 years (Figure 3-1).

Special effects resulting from Germany's reunification determined the development of the power plant fleet from 1990 to 1995. In 1990 all nuclear power plants in the new federal states were switched off and the capacities of East German lignite power plants (especially the industrial power plants) were substantially reduced. The capacities of hard coal power plants decreased significantly from 1990 to 2013, amounting to approx. 5 GW in total. However, a number of new hard-coal power plants commenced operation in 2014 and 2015, leading to a considerable increase in hard coal capacities. The gross capacities of gas-fired power plants has increased substantially in the last 25 years, by approx. 9 GW in total. In the course of the phase-out of nuclear power, the installed capacity of German nuclear power plants has decreased considerably since 2011.

However, the largest changes occurred with regard to power plants based on renewable energies. In the beginning of the 1990s, above all hydropower was relevant, albeit with relatively low capacities. As a result of the financing instrument of the German Renewable Energy Sources Act (EEG) there has been a huge increase in onshore wind energy and biomass since the turn of the millennium; from 2005 onwards there was also a huge expansion in photovoltaic (PV) capacity in particular. In 2012, the installed capacity of PV installations amounted to approx. 33 GW and was, for the first time, larger than the capacity of onshore wind power. Since 2013 there has also been an increase in the commissioning of offshore wind power capacities.

Figure 3-1: **Gross electricity generation capacities in Germany, 1990–2015**

Source: German Federal Ministry for Economic Affairs and Energy, calculations by Öko-Institut

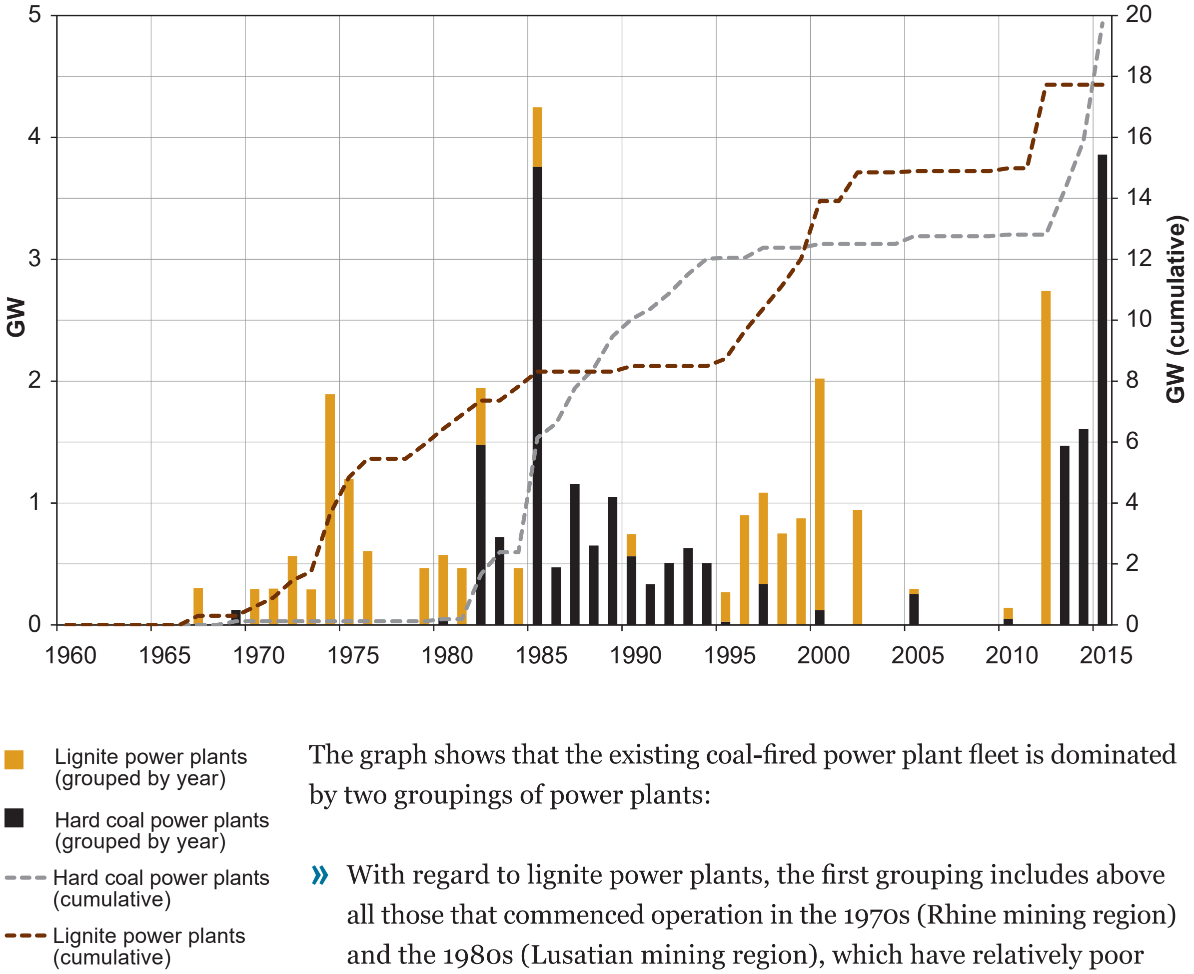


In view of the particular importance of coal-fired power plants, which account for approx. 45% of the total adjustable capacity of power plants in Germany's supply system, Figure 3-2 shows in more detail the age structure of German coal-fired power plants for which long-term operation is currently planned.[3] The anticipated decommissioning of power plant capacities is considered in the calculations, which is to occur, on the one hand, in the course of transferring 2.7 GW of lignite power plant capacity to security standby (approx. 16% of lignite power plant capacity) and, on the other hand, within the scope of the market-driven shutdown of approx. 9 GW that is expected by 2020 above all in the hard coal power plant fleet (which corresponds to about a third of hard coal power plant capacity).

3 In contrast to Figure 3-1, Figure 3-2 shows the net capacity, i.e. the capacity available to the electricity system supply after the own consumption of the power plants has been deducted and on which the modelling activities are based. For the historical time series, only data on gross capacity is available from the statistics, which also includes the own consumption needed for operation of the power plant.

Figure 3-2: **Age structure of net electricity generation capacities based on lignite and hard coal in Germany (without shutdowns planned up to 2020)**

Source: German Federal Network Agency, calculations by Öko-Institut



The graph shows that the existing coal-fired power plant fleet is dominated by two groupings of power plants:

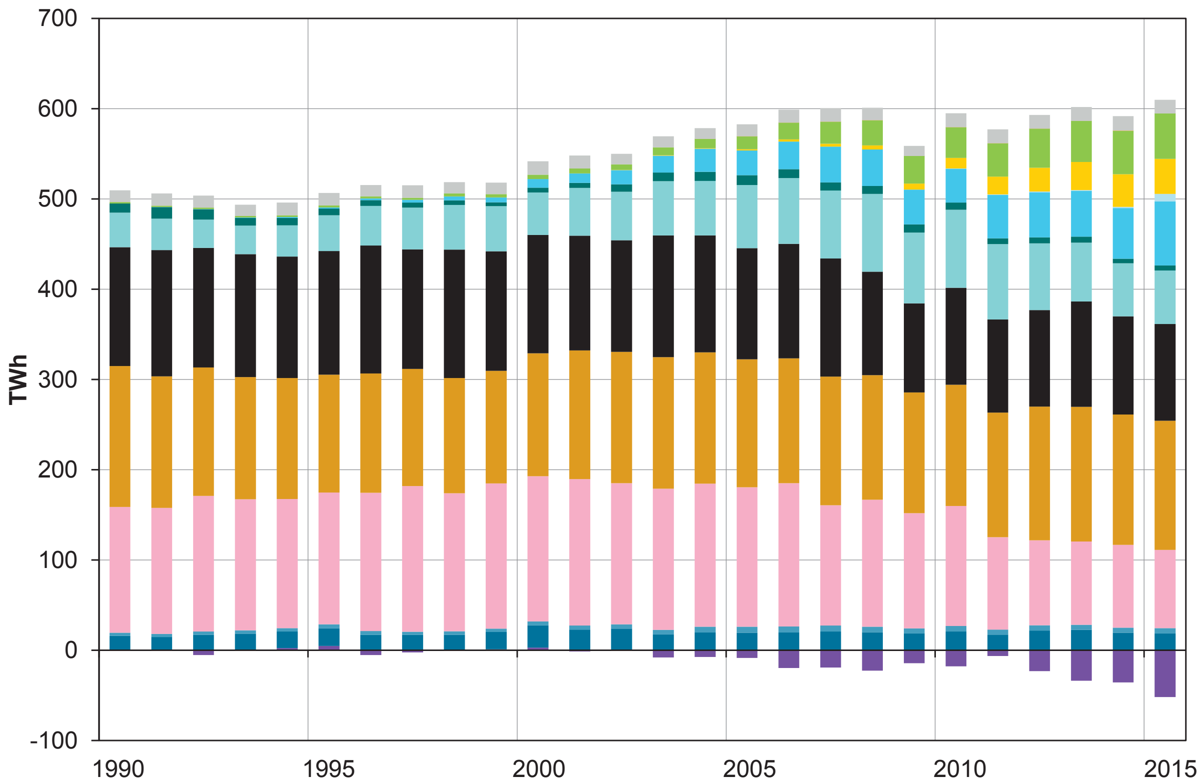
» With regard to lignite power plants, the first grouping includes above all those that commenced operation in the 1970s (Rhine mining region) and the 1980s (Lusatian mining region), which have relatively poor efficiencies and thus very high CO_2 emissions. The second grouping contains the lignite power plants that began operation in the 1990s and those shortly after the millennium, first of all in the new federal states and then, in 2002 and 2012, in the Rhine region. These lignite power plants have considerably better efficiencies, but still relatively high emissions due to their fuel type.

» With regard to hard coal power plants, the first grouping contains the power plants that started commercial operation between the early 1980s and the mid-1990s, have relatively poor specific CO_2 emissions and, based on their relatively low utilization currently and in the foreseeable future, make a disproportionately low contribution to CO_2 emissions. The second grouping comprises hard coal power plants that have commenced operation since 2013, have relatively good efficiencies and, due to their high capacity utilization and to the CO_2 intensity of hard coal, have relatively high emission levels.

The cumulative capacities of the different start-up years illustrate the problematic age structure of both the lignite and the hard coal power plant fleets. Approx. 51% of the hard coal-fired power plants and approx. 48% of the lignite power plants for which further operation is planned will have a service life of 30 years or more in 2020. Not focusing on these very old installations will prevent strategies for accelerating emission reductions in the electricity sector from succeeding. The concentration of power plant capacities in the groupings mentioned above must be carefully considered in the development of the emission reduction strategies and in the development of regulatory instruments.

Figure 3-3: **Net power generation in Germany, 1990–2015**

Source: German Federal Ministry for Economic Affairs and Energy (BMWi), Federal Statistical Office (StBA), German Federal Association of the Energy and Water Industry (BDEW), calculations by Öko-Institut



In the last 25 years, net electricity generation[4] in German power plants (Figure 3-3) has developed along with the capacity development, but has also been strongly influenced by changes in the market environment:

- Net electricity generation from nuclear power plants in Germany reached its historical apex in 2001, at approx. 162 TWh (also taking into account electricity generation from nuclear power plants in East and West Germany before reunification) and has decreased since then due to the phase-out of nuclear energy.

- The net electricity generation of lignite power plants has increased again considerably since the turn of the millennium, following small decreases in the course of the 1990s. It is currently at the same level it was in 1991 and 1992 and only slightly below its level of 1990, the year of Germany's reunification.

- Net electricity generation from hard coal-fired power plants rose slightly in the 1990s and fell substantially after the millennium, by almost 20%.

- Net electricity generation of German natural gas power plants rose sharply from the beginning of the 1990s onwards. In 2010 and 2011 it reached about 2.3 times the level it had in the early 1990s. However, due to unfavourable market conditions (high price differences between natural gas and coal, low CO_2 prices), electricity generation based on natural gas fell again in the subsequent years, by about 30%. It is currently mainly limited to the combined heat and power plants of the public utilities, the own consumption of industry and in other segments close to the points of consumption.

- There has been a huge increase in net electricity generation based on renewable energies since the beginning of the 2000s; its total capacity amounted to 151 TWh in 2013, which exceeded the level for lignite production for the first time (2013: 149 TWh). In 2015 its capacity reached approx. 187 TWh. Electricity generation from renewable energies is clearly dominated by onshore wind power (just under 12 % of total net electricity generation), biomass (approx. 8 %)

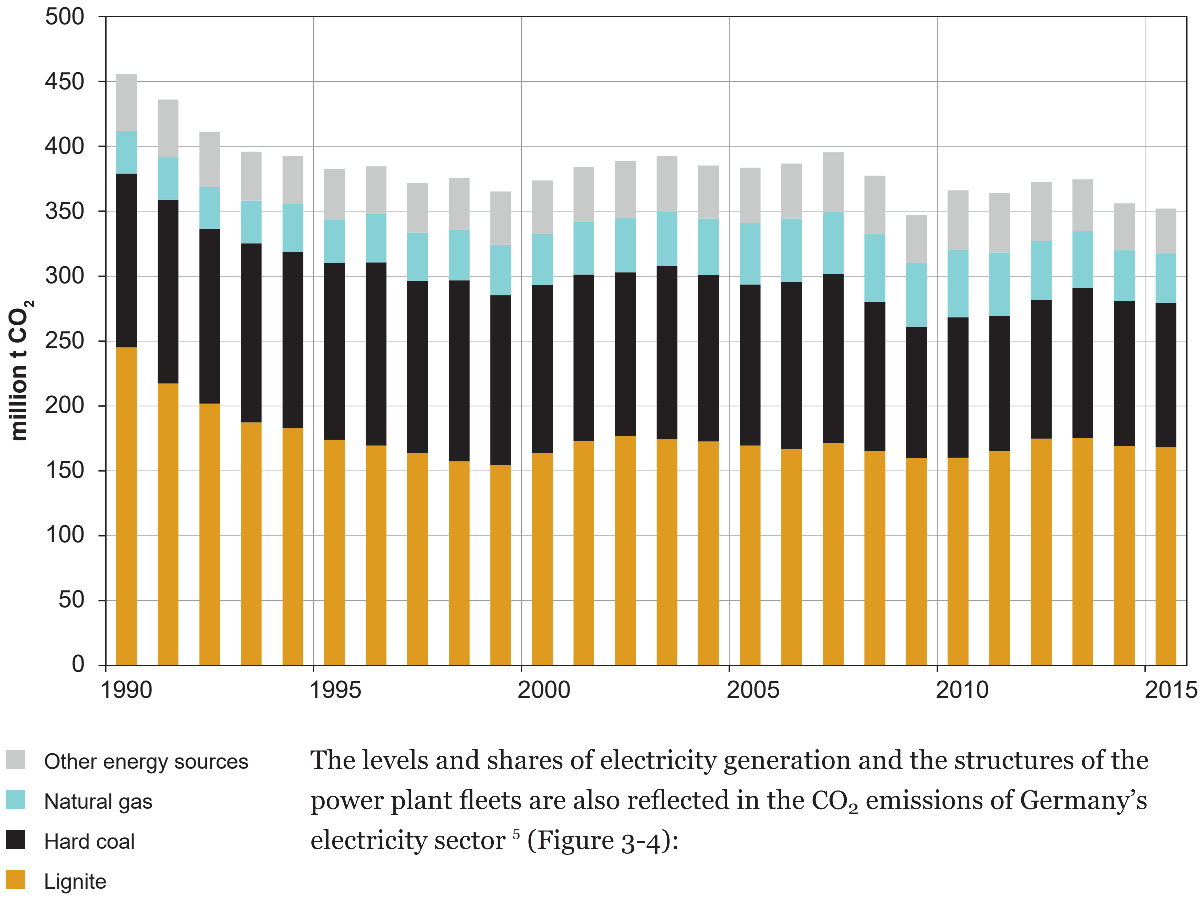
4 In the following and in the modelling, net electricity generation is shown, i.e. the total (gross) electricity generation of the respective power plants with their own consumption deducted. For net electricity generation, there is only some differentiation by fuel (for the power plants of general electricity supply) in official energy statistics. The net electricity generation data differentiated by fuel that was used in the present study was compiled by Öko-Institut as consistent electricity quantities based on all available data sources.

and PV installations (above 6%). Offshore wind power currently constitutes slightly more than 1% of total net electricity generation, with a strongly upward trend. Geothermal energy still plays a minor role, with a share of 0.02% of the total net German electricity generation.

» Lastly, the huge increase in Germany's net electricity exports since the millennium is relevant. Given the contribution margins of electricity generation and the current marginal cost structure, these exports are above all attributable to electricity generation plants with relatively low fuel costs and high CO_2 emissions, i.e. above all coal-fired power plants.

Figure 3-4: **CO_2 emissions of electricity generation plants in Germany, 1990–2015**

Source: German Federal Environment Agency, calculations by Öko-Institut



Data for 2015 is provisional and partly estimated

The levels and shares of electricity generation and the structures of the power plant fleets are also reflected in the CO_2 emissions of Germany's electricity sector [5] (Figure 3-4):

5 In the present study, the CO_2 emissions of Germany's electricity sector are defined according to the so-called plant concept. According to this concept, CO_2 emissions released into the atmosphere generated in electricity generation plants are attributed to the electricity sector, even if co-products like heat are also produced in these plants. The emissions are not attributed to the products themselves in the calculations (as would be the case when using the so-called production concept); this would make little sense given the questions handled in the present analysis.

- The CO_2 emissions of the German electricity sector currently (i.e. in 2015) amount to approx. 352 million tonnes, which is approx. 23% below the 1990 level and 8% below the 1995 level (1995 can be used as a robust reference year for classifying the special effects specific to Germany's reunification). The share of electricity sector emissions in total greenhouse gas emissions (taking into account the non-CO_2 greenhouse gases and the emissions of fuel quantities tanked in Germany for international transport) currently amounts to approx. 37%, which is well above the levels of 1995 (33.5%) and even 1990 (36%).

- The largest share of the current emissions of Germany's electricity sector, at 48%, is currently attributable to lignite power plants. The corresponding share of total greenhouse gases emitted by the electricity sector from 1990 onwards is just below this level, at 46%.

- The second largest emission share of Germany's electricity sector is attributable to electricity generation from hard coal power plants, which currently has a share amounting to approx. 32%; its share for the entire period of 1990 to 2015 is similar.

- Natural gas-fired electricity generation has a share of approx. 11% of the current and cumulative emissions of the electricity sector since 1990.

- The emissions of power plants operated with other fossil fuels (mainly blast furnace gases of the steel industry, petroleum products and non-organic waste) are at a similar level. The current share amounts to approx. 10%; its share for the entire period of 1990 to 2015 is approx. 11%.

Strategies for substantial emission reductions in Germany's electricity sector unquestionably need to address the approx. 80% share of coal-fired electricity generation in the sector's emissions as a high priority.

4 A climate-fair carbon budget for Germany's electricity sector

4.1 Global carbon budget

National and sectoral climate protection strategies and policies are – especially since the Paris Agreement was adopted and came into force – judged by whether they are compatible with the overarching goals laid down in the agreement, i.e. above all with the limit on the increase in global average temperature to (clearly) below 2°C compared to pre-industrial levels. In the diverse analyses conducted within the scope of climate modelling, emission budgets have proved to be a pragmatic approach that can be used to establish a link between global warming and the development paths for greenhouse gas emissions and provide a guiding basis for action. These analyses focus above all on the cumulative emissions of the most important greenhouse gas carbon dioxide (CO_2) over specific periods of time; this constitutes a robust indicator for different emission developments.[6]

Table 4-1: **Global CO_2 emissions and global carbon budget**

Source: Intergovernmental Panel on Climate Change (IPCC), PRIMAP, calculations by Öko-Institut

	CO_2 emissions	Global carbon budget		
	1870 to 2010	from 2011	2011 to 2014	Remaining budget
	Gt CO_2			
1.5°C in 66% of model runs	1,914	400	160	240
1.5°C in 50% of model runs	1,914	550	160	390
1.5°C in 33% of model runs	1,914	850	160	690
2°C with 66% probability	1,914	1,049	160	890
2°C with 50% probability	1,914	1,159	160	1,000
2°C with 33% probability	1,914	1,449	160	1,290
3°C in 66% of model runs	1,914	2,400	160	2,240
3°C in 50% of model runs	1,914	2,800	160	2,640
3°C in 33% of model runs	1,914	3,250	160	3,090

6 In order to ensure consistency with the work of the IPCC on which the following is based, the present study considers only CO_2 emissions and not the other greenhouse gas emissions. Given the clearly dominant role of CO_2 emissions in the context of the total (energy-related) emissions of Germany, this is a helpful and robust approach.

Table 4-1 provides a summary of some basic data relevant to the analyses on determination of the emission budgets:

- In the 5th IPCC Assessment report, a large number of models were evaluated. These enable the probabilities of carbon budgets for the time frame from 2011 to 2050 to stay below the limit on the 2°C increase in global mean temperature compared to pre-industrial levels (IPCC 2013a, p. 27).

- A probability assessment of this kind cannot be conducted for other temperature limits. However, the information presented in the 5th IPCC report on the number of model runs in which the temperature levels remain below the limits, enables at least an approximate classification of the different emission budgets (IPCC 2014, p 64).

- The long series for the development of CO_2 emissions (including those from land use and land use change) were taken from the database of the PRIMAP project and evaluated (Gütschow et al. 2016). Global emissions of 2,074 billion tonnes of CO_2 were determined for 1870 to 2014, of which over a quarter (25.9%) stems from 2000 to 2014 and almost 40% (39.6%) from 1990 to 2014. This demonstrates the great impact that the emissions development of the last 25 years has had on cumulative greenhouse gas emissions and the central importance of avoiding further delays in implementing emission reductions in order to enable an effective climate protection. Although the CO_2 emissions from land use and land use change have only a 6.3% share in the cumulative CO_2 emissions from 1870 to 2014, they currently account for about 13.3% of annual CO_2 emissions. The most substantial share of CO_2 emissions is attributable to energy-related emissions.

- It can only be expected with a probability of 66% that the increase in global temperature is limited to below 2°C if the CO_2 emissions arising from 2015 onwards do not exceed a total of 890 billion t CO_2. For lower probabilities of 50% and 33% respectively, the carbon budgets are correspondingly higher, at 1,000 and 1,290 billion t CO_2. For temperature increase limits of 1.5°C. and 3°C, approximate reference levels are derived from the available model analyses and shown in Table 4-1. Limiting the global temperature increase to below 1.5°C with a relatively high probability leads to a global carbon budget of approx. 240 billion t CO_2 from 2015 onwards; the carbon budget for the 3°C limit amounts to 2,240 billion t CO_2.

- A comparison with the current annual emissions of approx. 40.6 billion t CO_2 worldwide shows that huge emission reductions will be necessary within a relatively short time frame to keep the increase in global temperature below the 2°C and 1.5°C limits.

- If the global temperature increase is kept below 2°C there is a relatively high probability (66%) that the current emission levels could be maintained for 22 years. If a linear emissions trend is assumed, global CO_2 emissions would have to be reduced to net zero within 44 years. Otherwise, in the subsequent years, substantial quantities of CO_2 would have to be removed from the atmosphere with technologies that have currently been barely tested (carbon capture from biomass production or direct air capture, combined with safe carbon storage, e.g. in geological formations).

- Adherence to the limit in global temperature of 1.5°C could be achieved with a relatively high probability, based on the available data, only if emissions continue unchanged from today's levels for 6 years. If a linear reduction of global emissions is assumed, global decarbonization would be necessary within 12 years or huge volumes of CO_2 would need to be removed from the atmosphere in the following years.

The following analyses are based on the working hypothesis that cumulative global CO_2 emissions should not exceed 890 billion t CO_2 from 2015 onwards. On this basis, the increase in global temperature could, with a high probability, remain at least below 2°C compared to preindustrial levels.

4.2 A climate-fair carbon budget for Germany

Based on a global carbon budget of 890 million t CO_2 from 2015 onwards, a corresponding emissions budget can be derived for Germany. Transparent derivation of national emission budgets based on clear criteria is a useful and reasonable approach to determining Germany's fair share of use of the global resource, the atmosphere. Such an approach can be used to prevent emission reduction measures in legislation areas that have only relatively small shares of global emissions at national or regional level, meaning that they can make only correspondingly small contributions to global emission reductions. These evaluation metrics are not only in the interests of a legally binding concept (which currently does not exist and is not foreseeable at present), but also in terms of ensuring the consistency of national and regional activities.

The key question in the derivation of national carbon budgets is what the principles and criteria are for breaking down the global emission budget to reference areas such as a country or region. Among the many conceivable and discussed perspectives, four approaches are especially significant:

1. The global carbon budget can be divided on current emission levels (also as an approximation for prosperity levels, etc.). This approach ultimately represents the principle of the protection of vested rights.

2. An alternative option is to divide the global budget on an equality basis, i.e. based on population numbers, although different emphases can be achieved depending on whether current population numbers are used or projections of future populations should be considered. In essence, such an approach follows the principle of equality of opportunity.

3. A third option is to allocate the global budget based on the performance-related principle. Countries or regions with a higher performance capacity (also in terms of emission reductions) or higher prosperity would be allocated a smaller share of the global budget under this approach, if other countries of the world are to be given the chance to catch up in these respects. This option particularly brings to bear the challenges of, for example, how to handle the very different methods for measuring economic performance and prosperity (gross domestic product as, in some cases, a controversial indicator, adjusting values based on exchange rates or purchasing power parities, etc.), future growth dynamics and also the corresponding uncertainties.

Another issue of great importance is how to consider past utilization of the atmosphere. There needs to be a discussion on whether historical emissions should be taken into account in determining national emission budgets and, if so, what time scale is appropriate. Here, too, different approaches are conceivable:

- An extreme approach would be to consider all historical emissions, e.g. since the beginning of industrialization. In the case of Germany, historical emissions totalling 87 billion tonnes CO_2 from 1870 to 2014 would have to be taken into account as prior utilization of the total emission budget. To keep within the 2°C limit with a probability of 66%, the global emission budget, taking into account historical emissions, amounts to a total of 2,963 billion t CO_2 (890 plus 2,074 billion t CO_2) up to 2050: on this basis Germany would already have used 3% of the global emission budget available up to the middle of this century.

- An alternative approach would be to take into account historical emissions from the point in time when the dangers of man-made (anthropogenic) climate change were widely addressed as a challenge, regardless of whether measures were immediately adopted or not. The year 1990 could be chosen as a useful reference point. For Germany, historical emissions of approx. 22 billion t CO_2 would have to be considered, corresponding to approx. 1.3% of the total global emission budget available for 2050.

- Another option would be to consider emissions from the time at which the international community as a whole committed to binding climate protection targets. The point of reference here would be, for example, the adoption of the Paris Agreement in 2015. In effect, only the future release of CO_2 into the atmosphere (i.e. that which can still be influenced) would count towards the emissions budget remaining for 2015 to 2050.

As these options show, there are a large range of approaches to determining national or regional emission budgets. It should be pointed out, however, that not all combinations of reference period and distribution key are useful.[7]

7 For example, it is not very consistent to combine emission budgets for future emissions with distribution keys based on the preservation of vested interests. It would be essential to consider historical emissions, at least in part, in order to achieve an acceptable distribution of the global emission budget.

Table 4-2 shows the results of using different distribution keys on carbon budgets for different temperature limits and the corresponding probability of keeping within these limits, without considering historical emissions. In terms of the global emission budget, Germany's "rights of use" calculated on this basis range between 0.8% and 2.0%.

Table 4-2: Global CO_2 emissions and national carbon budget (without considering historical emissions)

Source: Intergovernmental Panel on Climate Change (IPCC), PRIMAP, World Bank, UN WPP, Federal Statistical Office, calculations by Öko-Institut

	Carbon budget global	Germany's carbon budget		
		Emission share	Population	
	from 2015		Current	2050
	Gt CO_2			
1.5 °C in 66 % of model runs	240	4.7	2.7	1.9
1.5 °C in 50 % of model runs	390	7.7	4.4	3.1
1.5 °C in 33 % of model runs	690	13.6	7.7	5.4
2 °C with 66 % probability	890	17.5	9.9	7.0
2 °C with 50 % probability	1,000	19.6	11.2	7.8
2 °C with 33 % probability	1,290	25.3	14.4	10.1
3 °C in 66 % of model runs	2,240	44.0	25.1	17.5
3 °C in 50 % of model runs	2,640	51.9	29.5	20.7
3 °C in 33 % of model runs	3,090	60.7	34.6	24.2
Reference levels for calculating German share		**CO_2 emissions**	**Population**	
		2015	2015	2050
		Gt CO_2	**Million**	
World		40.644	7.347	9.725
Germany		0.799	82	76
Germany's share		2.0 %	1.1 %	0.8 %

Additional model calculations that consider historical emissions and the 2°C limit on the global temperature increase show that Germany's available emission budget would already have been exhausted if historical emissions covering very long periods (e.g. 1870 to 2014) were considered. If historical emissions over shorter periods (e.g. from 1990 to 2014) are taken into account and the increase in global temperature is assumed to be safely below 2°C, only distribution approaches that are considerably above Germany's population share in the global population would mean that it would be possible to count future emissions against the carbon budget, i.e. the carbon budget would not have been completely or very extensively tapped by historical emissions.

In the overarching ranking of all aspects, it was agreed with the contracting authority that in measuring the fair contribution to global climate protection that Germany should make by reducing its future CO_2 emissions, historical emissions should not be considered and the remaining global emission budget should be divided on a global per capita basis. Germany's current population (as of 2015) serves as a robust reference value for this per capita distribution. Germany's contribution to achieving global climate protection goals above this distribution would have to be met via financial transfers, i.e. by financially enabling additional emission reductions in regions in which the quantity of historical emissions is lower or the development of CO_2-intensive capital stocks is less highly advanced or can still be effectively avoided.

Based on a global emissions budget of 890 billion t CO_2 from the year 2015 onwards and Germany's population share in the world population in 2015 (1.1%), Germany's emission budget is calculated as approx. 9.9 billion t CO_2 up to 2050. It should also be noted that the determination of this budget is also relatively balanced in view of the fact that both calculation approaches are advantageous for Germany (no consideration of historical emissions, using the current population level as a reference) and for global balancing (per capita distribution) have been used.

4.3 Derivation of the carbon budget for Germany's electricity sector

In the operationalization of a sectoral emission budget, the national emission budget must still be divided among the respective sectors, i.e. this means in the scope of the present analysis that the emission budget for the electricity generation sector needs to be defined. With emission budgets that necessitate the reduction of (net) CO_2 emissions almost to zero, there is a comparatively low degree of freedom in designing this distribution. The crucial questions concern the lifetime of capital stocks, the necessary lead times for innovation processes and infrastructure development, i.e. the time frame for emission reductions and their costs. The pragmatic approach of using current emission levels as the basis for distributing the sectoral emission budget is also useful given the diverse forecasting uncertainties and the possibility of creating flexibility and optimization potentials during the development of the relevant policy instruments.

Table 4-3 shows the emission budgets that result for the electricity sector as the sector with the largest share of emissions in Germany's total CO_2 emissions, based on current emissions data. Germany's electricity sector currently accounts for approx. 42% of the country's total CO_2 emissions[8]. Based on a proportional distribution of the national emission budget derived in chapter 4.2, an emission budget of approx. 4.2 billion t CO_2 would be available for the future emissions of electricity generation in Germany.

8 Two methodological conventions should be pointed out here. In the present study, the emissions of electricity generation are considered on the basis of the so-called "plant concept". The emissions of the electricity sector therefore include all greenhouse gases emitted by electricity generation plants, irrespective of whether they produce further co-products (particularly heat) in addition to electricity. Thus, there is no synthetic division of emissions by electricity and heat generation. Furthermore, the CO_2 emissions of international air transport and maritime transport resulting from the quantities of fuel tanked in Germany are included in Germany's total emissions.

Table 4-3: **National carbon and electricity sector budgets for Germany**

Source: German Federal Environmental Protection Agency, calculations by Öko-Institut

	Carbon budget national	CO_2 emissionas Elec. sector	Carbon budget Elec. sector Emission share	
	from 2015	2015	Current	Reduced
	Gt CO_2			
1.5 °C in 66 % of model runs	2.7	0.352	1.1	1.1
1.5 °C in 50 % of model runs	4.4	0.352	1.9	1.7
1.5 °C in 33 % of model runs	7.7	0.352	3.3	3.1
2 °C with 66 % probability	9.9	0.352	4.2	4.0
2 °C with 50 % probability	11.2	0.352	4.7	4.5
2 °C with 33 % probability	14.4	0.352	6.1	5.8
3 °C in 66 % of model runs	25.1	0.352	10.6	10.0
3 °C in 50 % of model runs	29.5	0.352	12.5	11.8
3 °C in 33 % of model runs	34.6	0.352	14.7	13.8

If it is still taken into account that CO_2 emissions from industrial processes in particular are challenging in the context of emission reductions and that the electricity sector would have to assume an additional reduction in emissions on this basis, the electricity sector's share in Germany's national emission budget amounts to only approx. 40 %.

In view of this and in the context of a relatively probable adherence to the 2°C temperature increase limit, the German electricity sector has an emission budget of between 4.0 and 4.2 billion t CO_2 until the middle of the century.

5 Framework assumptions for modelling paths for the phase-out of coal in Germany

5.1 Fuel and CO_2 prices

The assumptions for future fuel and CO_2 prices have an influence on both the utilization of power plants and their general profitability, i.e. covering all relevant costs and making a profit. At the same time, the future development of these parameters is subject to high uncertainties. Scenarios must therefore be founded on well-chosen assumptions for these input parameters and have the character of conditional statements ("if, then…") rather than forecasts. The assumptions must be chosen based primarily on the specific purpose of the analysis at hand. For the present study, this purpose is to achieve the climate protection targets and to create appropriate framework conditions for this. In order to generate robust findings and to derive a targeted framework of action for climate and energy policy, the framework conditions for the scenario analyses have to be chosen carefully so that the defined targets can also be achieved if global energy market developments are unfavourable.

The framework assumptions for the prices of fuel imports and exports are based on, firstly, the oil price projection in the reference scenario of the Annual Energy Outlook (AEO) 2014 provided by the Energy Information Administration (EIA) of the US Department of Energy (EIA 2014).
In the context of the current prices or more recent projections, this price path has a relatively high fuel price: for 2020, 2030 and 2040, AEO 2014 assumes prices of 101, 124 and 148 US$ per barrel of Brent crude oil, based on 2015 prices. More recent projections undertaken by the EIA, e.g. of the Annual Energy Outlook 2016, are significantly below the 2014 projections, at 77, 104 and 136 US$/bbl (2015 prices) respectively. The current World Energy Outlook (WEO) 2016 of the International Energy Agency (IEA 2016) assumes for 2020, 2030 and 2040 crude oil prices of 82, 127 and 146 US$/bbl and, in the case of very ambitious global climate protection policies, 73, 85 and 78 US$/bbl (all values based on 2015 prices).

Against the background of the uncertainties and ranges of projections made particularly evident by current projections, and under the premise that the present analyses should enable robust policy approaches to be derived, it seems reasonable to assume a price environment with oil prices of approx. 125 US$/bbl for 2030 and approx. 150 US$/bbl for 2050.

The price levels for natural gas, hard coal and heating oil were derived from projections for crude oil prices. They are based on econometric analyses of the relationship between the respective prices, which allow relatively robust explanatory patterns to be derived for long-term trends. The prices at which the fuels including their transportation are available were also derived from the wholesale market prices determined in this way.

Short-term marginal costs of lignite production amounting to 1.50 €/ MWhth were used to calculate the lignite prices that are ultimately not dependent on developments on the global fuel markets. However, it should also be taken into account that the full costs of lignite production tend to amount to around 6 €/ MWhth.

In terms of the costs of the emission allowances of the European Union Emissions Trading System (European Union Allowances – EUA), the assumed development can be considered the most realistic estimate possible from today's perspective. Overall the influence of CO_2 costs on power plant utilization decreases as the share of renewable energies in electricity generation increases and the fossil capacities still operating in the system decrease. Nevertheless, CO_2 costs are a crucial framework condition for the emission intensity of the remaining fossil-fired power plant fleet and thus for the emission development of the electricity system.

Table 5-1 shows the fuel and CO_2 prices assumed in the modelling ("Challenging framework conditions for climate protection") and is contrasted for information purposes with a price environment in which at least a share of the (necessary) emission reductions are predominantly market-driven ("Beneficial framework conditions for climate protection"). In both cases, 2010 prices are taken as a basis.

Table 5-1: Development of fuel and CO_2 prices in a challenging and beneficial environment for climate policy (2010 price basis)

Source: European Energy Exchange (EEX), German Petroleum Industry Association (MWV), Energy Information Administration (EIA), calculations by Öko-Institut

		Actual	Projection						
		2015	2020	2025	2030	2035	2040	2045	2050
Challenging framework conditions for climate protection									
Emission allowances	€/EUA	7.1	10.0	20.0	30.0	40.0	47.0	54.0	60.0
Hard coal	€/MWh (H_u)	7.5	9.4	10.3	11.1	11.7	13.1	13.8	14.2
Natural gas	€/MWh (H_u)	13.8	22.3	24.9	27.8	31.4	36.1	38.5	39.6
Heavy fuel oil	€/MWh (H_u)	21.2	30.6	36.0	42.6	49.2	56.7	60.5	62.3
Lignite									
Marginal costs	€/MWh (H_u)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Full costs	€/MWh (H_u)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Beneficial framework conditions for climate protection									
Emission allowances	€/EUA	7.1	10.0	22.5	35.0	47.5	60.0	66.3	69.4
Hard coal	€/MWh (H_u)	7.5	7.7	8.2	8.3	8.1	8.4	8.6	8.6
Natural gas	€/MWh (H_u)	13.8	16.0	17.9	18.8	19.1	19.9	20.3	20.5
Heavy fuel oil	€/MWh (H_u)	21.2	21.5	24.4	26.7	27.9	29.2	29.9	30.2
Lignite									
Marginal costs	€/MWh (H_u)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
Full costs	€/MWh (H_u)	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0

The following considerations support understanding these comparatively high fuel prices as an energy market environment that is challenging for climate protection: for particularly CO_2-intensive lignite-fired power plants, higher revenues are generated on the electricity market from high hard coal and natural gas prices on the continental European electricity market, in which hard coal and partly also natural gas power plants determine the electricity price for the time being. The same applies to hard coal-fired power plants in the context of a high natural gas price; their revenues are also higher when the electricity price is comparatively high during the hours in which the natural gas power plants are price-setting. In a market environment in which the revenues are sufficiently high for many power plants to cover both the variable and the fixed costs and maintain a high utilization, market-related decommissioning of power plant capacity is rather unlikely. Comparatively high CO_2 emission levels arise under these framework conditions.

In the version of framework conditions that are challenging for climate protection, the costs of changing production from an old lignite to a new hard coal or natural gas power plant amount to approx. 41 and 46 € per tonne of CO_2 (€/t CO_2) for 2020 and 51 and 58 €/t CO_2 for 2030. The cost of switching production from a new lignite or hard coal-fired power plant to a highly efficient natural gas power plant is 88 and 50 €/t CO_2 for 2020 and 107 and 66 €/t CO_2 for 2030 respectively. With the emission allowance costs shown in Table 5 1, additional climate policy instruments would be necessary in such an environment in the short, medium and long-term to achieve ambitious emission reduction targets.

To enable classification of the necessity of these instruments, the challenging energy market environment for climate policy was compared with one that was beneficial for climate policy. The prices for hard coal and natural gas increase slightly over time, but remain at considerably lower levels; also the difference in price between hard coal and natural gas remains at a level that facilitates the switch to less CO_2-intensive power generation options. In such a market environment, the costs of a fuel switch from an old lignite to a new hard coal or natural gas power plant amount to 32 and 31 €/t CO_2 for 2020 and 35 and 38 €/t CO_2 for 2030 respectively. The shift in production from a new lignite or hard coal-fired power plant to a new natural gas plant would cost 43 and 30 €/t CO_2 in 2020 in such an energy market environment. For 2030 these costs increase slightly to 52 and 40 € but, a higher CO_2 price, would make it easier to achieve the climate policy targets. At the same time, such a situation would not make complementary measures obsolete since additional framework conditions would have to be created to promote the decommissioning of CO_2-intensive power plants if the fixed operating costs of the total power plant fleet can no longer be covered by the contribution margins.

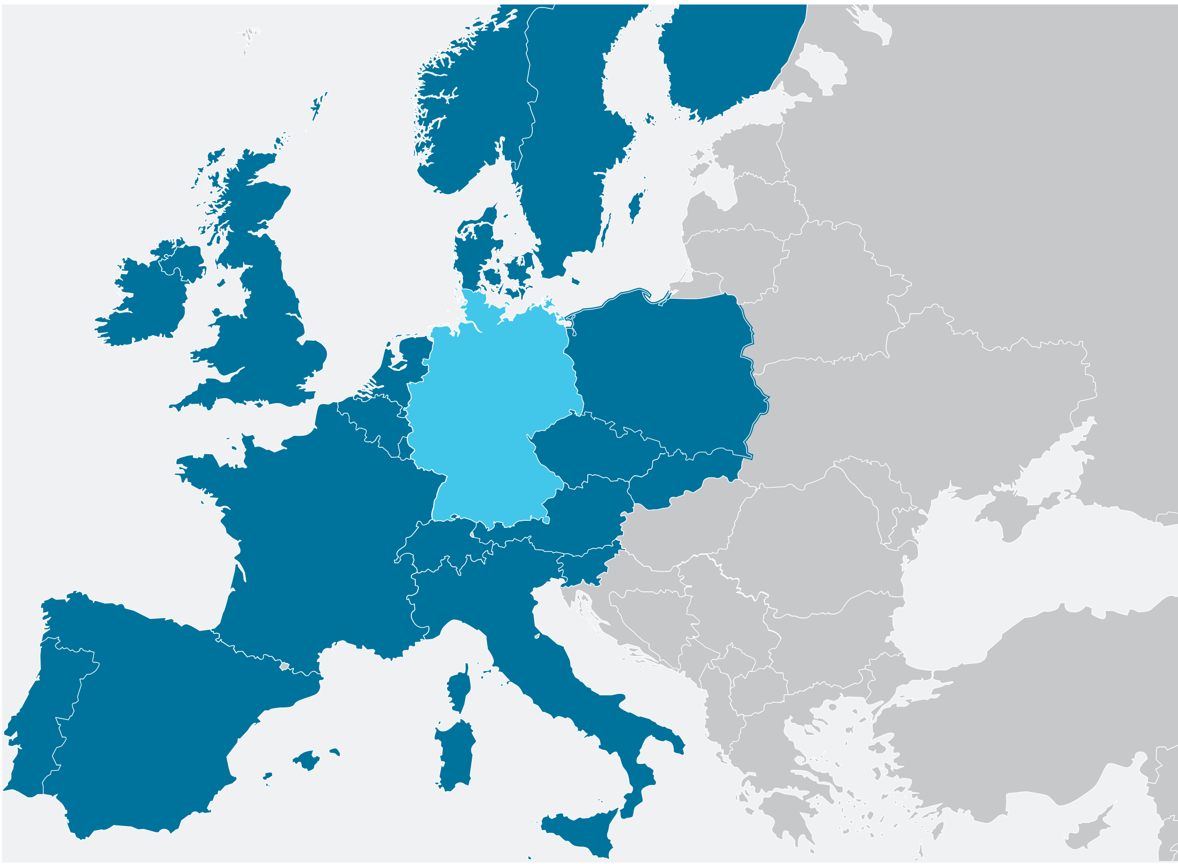
In any case, it should be noted that current developments on the global fuel markets do not point to the high fuel price path but, as of October 2016, they are already higher than the price levels assumed for 2020 in the scenario with challenging framework conditions for climate protection. In any event, the current CO_2 price is substantially lower than the levels assumed for 2020 in the version with framework conditions that are beneficial for climate protection.

5.2 Development of the power plant fleet outside of Germany

For the analyses of the development of the German electricity sector and related emission trends, it should be taken into account that the electricity markets in Europe are increasingly converging. The Network Development Plan for Germany, for example, assumes electricity exports to neighbouring markets of above 35 GW overall in 2030 (50Hertz et al. 2016a, BNetzA 2016). Framework conditions in the European market environment correspondingly have a large impact on the development in the German electricity market. In its climate and energy targets for 2030 (EC 2014, CONS 2014), the European Union has set the target of reducing greenhouse gas emissions by at least 40% by 2030 compared to 1990 levels. Furthermore, a binding target to increase the share of renewable energies to 27% of gross energy consumption and an indicative target of improving energy efficiency by 27% have also been adopted.

Figure 5-1: **Classification of region for modelling the electricity market**

Source: Prognos



However, the precise design of the policy targets has not yet been comprehensively determined, either for Europe as a whole or on a national level. As a result it is not yet possible to make detailed estimates of the effects on the electricity market in the individual Member States. The uncertainty associated with the development of the framework conditions in the European market environment is correspondingly high. Therefore, for the modelling of the electricity sector in Germany, assumptions need to be applied that cover a possible development beyond 2030 for other countries in Europe.

The model region shown in Figure 5-1 is used for the modelling. The detailed assumptions and results are shown for Germany's closest European neighbours – Austria, Switzerland, France, Luxembourg, Belgium, the Netherlands, Norway, Denmark, Sweden, Poland and the Czech Republic – due to their direct effect on Germany's electricity market. Germany's electricity neighbours are defined as the countries that already are – or in the case of Norway and Belgium, may be in future – directly connected to Germany's electricity grid.

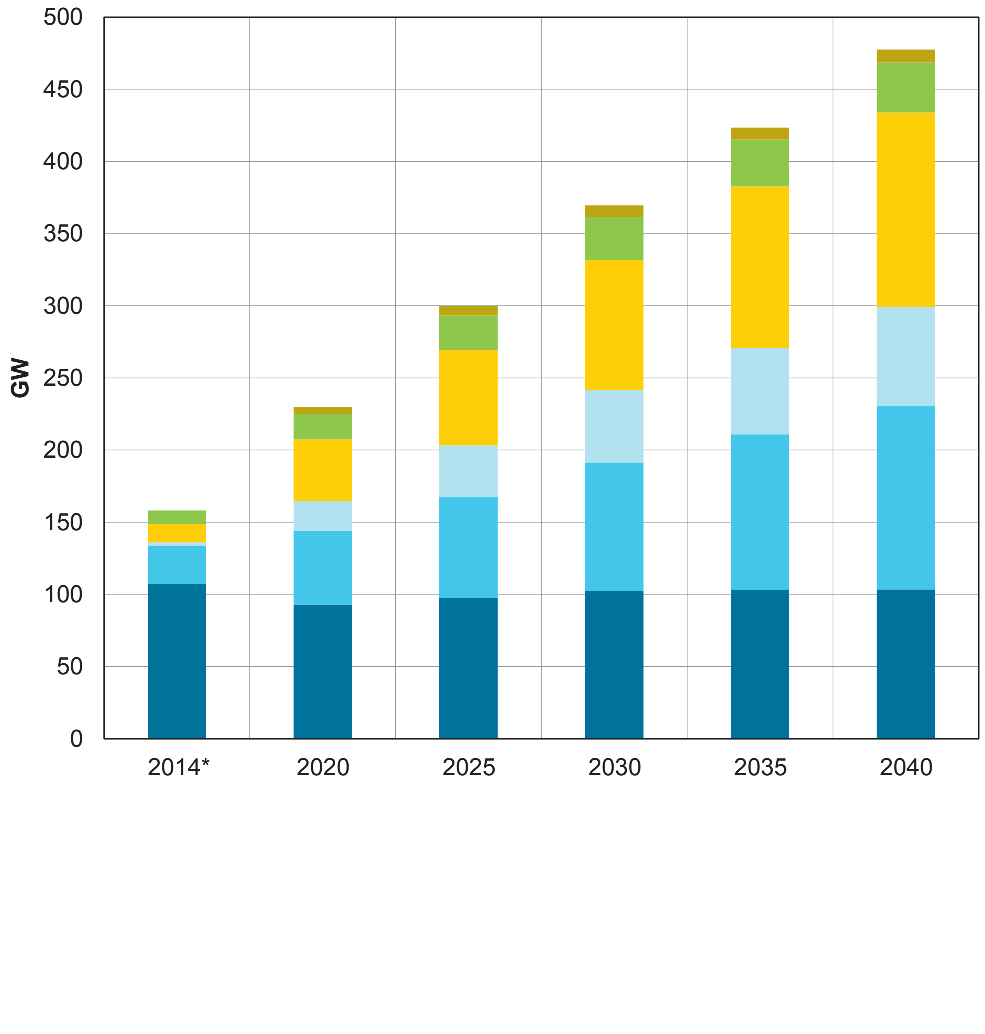
For this European environment, a transformation of the energy system by 2050 is assumed that is geared to the targets of energy transition (Energiewende), which comprises ambitious GHG reduction targets and the expansion of renewable energies. This is based on the assumption that an ambitious German climate protection policy is only realistic when embedded in the corresponding international and European environment.

For the expansion of renewable energies in Europe, scenarios are being developed by the European Association of Transmission System Operators (ENTSO-E) within the scope of analyses of system adequacy. These scenarios show different development paths. For the countries concerned, the installed capacities of the 2014 System Outlook and Adequacy Forecast (SOAF) were incorporated in the modelling (EntsoE 2014). SOAF Vision 4 has been used up to 2030 for all renewable energies, with the exception of biomass. For biomass, lower available potentials are estimated based on more recent work conducted on sustainable biomass potentials (Öko-Institut and Frauenhofer ISI 2015); for 2030 only the values of SOAF Vision 3 were used. For the development up to 2050 the trends for the installed capacities are updated in such a way that for the countries concerned, approx. 80% of production capacities are based on renewable energies in 2050, in line with national expansion targets and potentials. Higher or lower shares may also result for individual countries.

Figure 5-3 shows the electricity generation quantities of the different energy sources that result from calculations considering typical plant utilizations, calculated on the basis of weather data with a regional resolution.

Figure 5-2: **Expansion of electricity generation capacities based on renewable energy among Germany's electricity neighbours, 2020–2040**

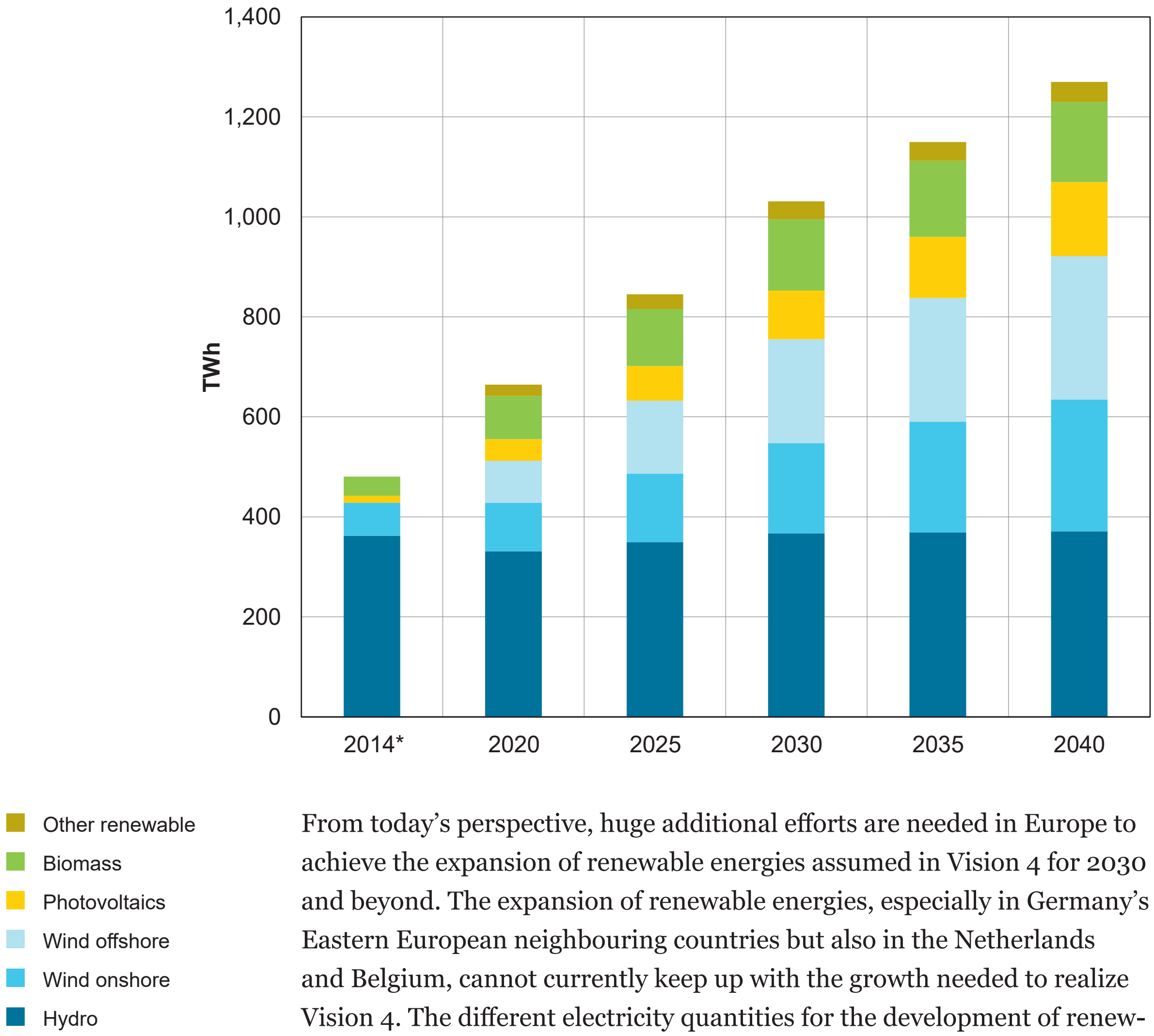
Source: Calculations by Prognos based on ENTSO E 2014



* *for 2014 hydro includes PSH capacities*

Figure 5-3: **Expansion of electricity generation based on renewable energy among Germany's electricity neighbours, 2020–2040**

Source: Calculations by Prognos based on ENTSO E 2014



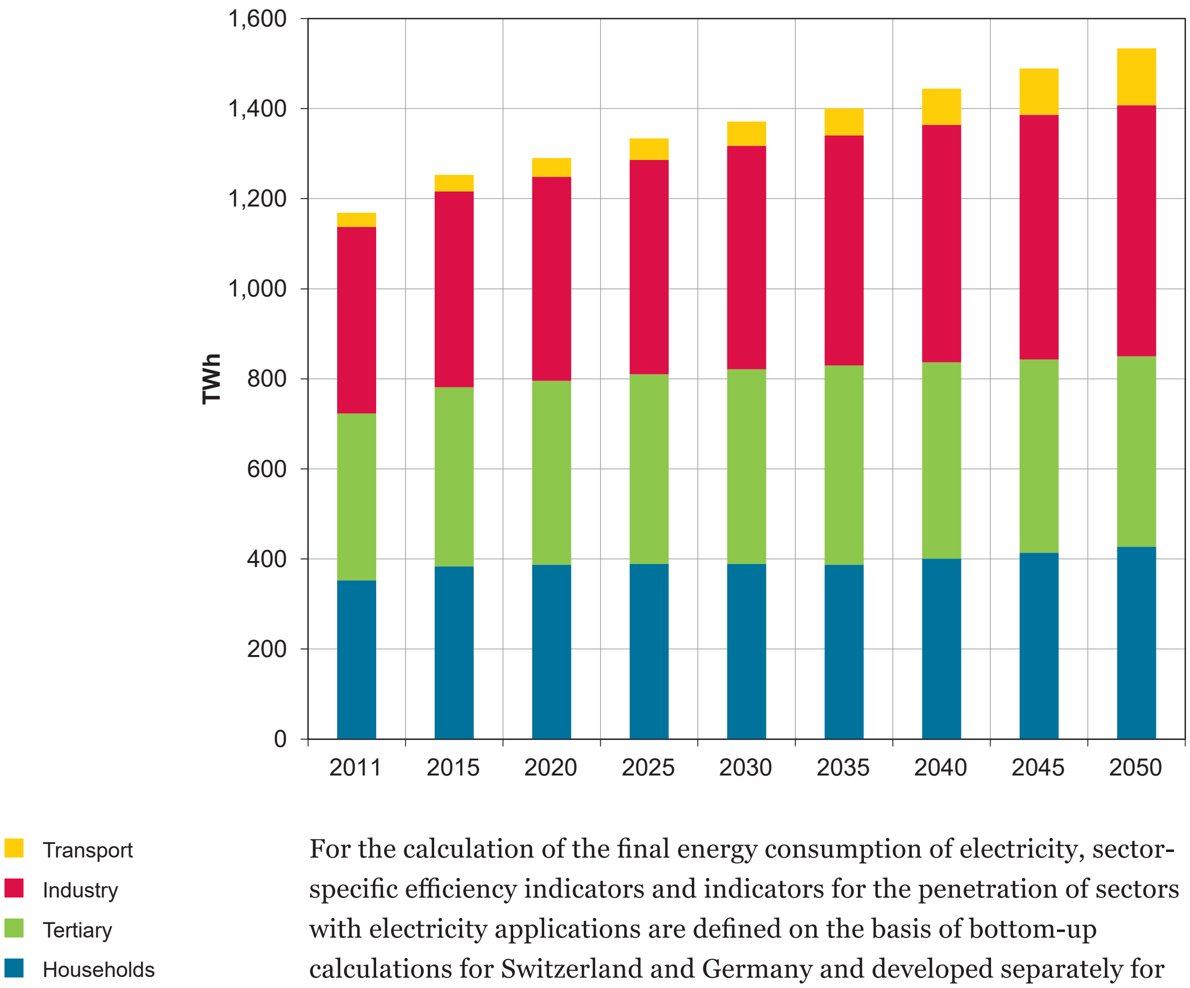
* *for 2014 hydro includes PSH capacities, wind onshore incl. wind offshore (if applicable)*

From today's perspective, huge additional efforts are needed in Europe to achieve the expansion of renewable energies assumed in Vision 4 for 2030 and beyond. The expansion of renewable energies, especially in Germany's Eastern European neighbouring countries but also in the Netherlands and Belgium, cannot currently keep up with the growth needed to realize Vision 4. The different electricity quantities for the development of renewable energies for the countries considered in the scenarios are shown in the annex.

The electricity demand of the countries included in the model is shaped by the development of the so-called electricity quantity drivers (population, economic growth, number of jobs, etc.) and the technical drivers (efficiency, number of applications, etc). The 2014 Prognos World Report was used for the demographic and economic data of the countries considered.

Figure 5-4: **Final energy demand for electricity among Germany's electricity neighbours, 2011–2050**

Source: Calculations by Prognos



For the calculation of the final energy consumption of electricity, sector-specific efficiency indicators and indicators for the penetration of sectors with electricity applications are defined on the basis of bottom-up calculations for Switzerland and Germany and developed separately for the remaining countries. Combined with the quantity drivers arising from the population and the economy, levels of sector-specific electricity demand are derived, which are shown cumulatively for the countries considered.

The results show that electricity demand in the European countries considered continues to increase in the future. Particularly the stronger economic growth in the long term and the stronger growth in electrification in all areas in Eastern and Southern Europe lead to an increase in electricity demand. This overcompensates the stagnation or even the slightly declining trend in the development of electricity demand in North Western Europe. In line with the assumption of energy transition, a stronger penetration of electrification and electrical applications is assumed in the transport and space heating sectors in the scenario.

The electricity demand of the countries considered increases by a total of approx. 300 TWh by 2050 compared to 2015 (Figure 5-4).

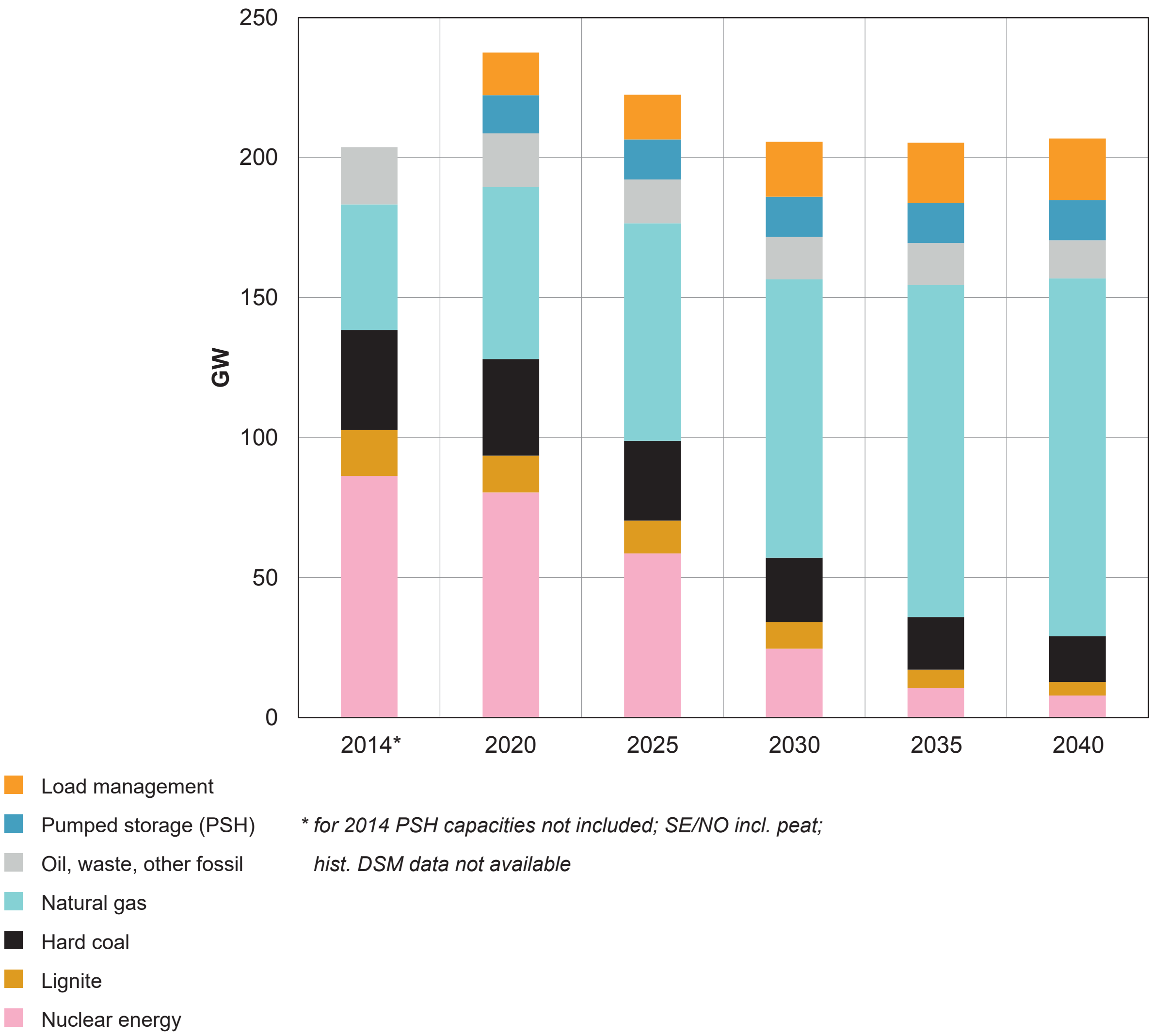
The results up to 2040 constitute an excerpt of the modelling of the European electricity market up to 2050. The results are thus the product of continuous modelling up to 2040 rather than calculations based on a reference year. The aim of this analysis is to simulate the development of Germany's power plant fleet dependent on corresponding developments in the other European countries considered and to determine the environment that results for the German electricity sector up to 2040. The growing interconnection of electricity markets in Europe means that the framework conditions in the European environment have considerable effects on national developments. An analysis of the European power market as a whole is essential for estimating the future development of CO_2 emissions in Germany's electricity sector. The results should be understood as a possible European energy transition scenario, which embeds Germany's energy transition in the related European environment by setting the regulatory framework (renewable energy policy, climate protection policy, market design, nuclear safety, etc.). This consistent approach to analysis also prevents certain beneficial (energy-economic) effects, only arising within the scope of decarbonization strategies for Germany, if other (EU) countries do not follow development paths of this kind.

In Europe, the structure of the conventional power plant fleet also changes substantially in the scenario considered (Figure 5-5). While the market shares of coal and nuclear power decrease considerably, the production capacity of natural gas power plants grows substantially. The largest uncertainty for the conventional power plant fleet in Europe concerns the expansion of renewable energies in Europe. Related to electricity demand, the growth in production capacities based on renewable energies is relatively large, which reduces the profitability of conventional large power plants substantially. Increases in natural gas power plant capacity are mainly to guarantee security of supply.

Another large uncertainty concerns the future of nuclear energy in Europe. Nuclear power plants that are currently in operation are already approx. 30 years old on average. In addition to Germany, Switzerland, Belgium and Sweden are currently planning to phase out nuclear energy in the medium term. France is also planning to reduce substantially their dependence on nuclear energy. There is nevertheless considerable uncertainty regarding the lifetime of the power plants in the existing nuclear power plant fleet. In addition, the costs of retrofitting and the tightening of safety standards within the EU are also unclear. It is assumed that the 30 to 35 year lifetime[9] of nuclear power plants that was planned when they commenced operation can be increased to 44 years in France and to 45 years in the other countries. Comprehensive investments in a further extension of plant lifetime beyond this or the construction of new power plants in addition to the known projects cannot be realized economically. As a consequence, the installed capacities of the nuclear power plant fleet decrease by almost two thirds up to 2030 in this scenario. In 2040 less than 10 GW of nuclear power plant capacity is installed in Germany's neighbouring countries.

Figure 5-5: **Development of installed conventional power plant capacity among Germany's electricity neighbours, 2020–2040**

Source: Authors' own calculations



9 See Prognos AG 2009, p. 21: "In contrast, a forecast of the reactor manufacturer Siemens assumes an average technical lifetime of 30 to 35 years."

The development in other countries in Europe has a substantial effect on the merit order and thus on the utilization and profitability of the power plant fleet in Germany. While nuclear power plants and renewable generation plants are more likely to be placed above the hard coal and lignite power plants in the overall European merit order, natural gas power plants are mostly located below the lignite power plants in the merit order.

Electricity generation in other European countries develops according to capacity development. The capacities of natural gas power plants increase substantially; above all, these capacity increases are to guarantee security of supply. In 2040 natural gas-fired power plants have fewer than 2,000 full load hours. This is due to the high level of electricity generation based on renewable energies. Up to 2030, natural gas production increases substantially due to the decrease in nuclear power in other European countries, partly because the assumed expansion of renewable energies is initially not sufficient to compensate the decrease in nuclear power. In total, conventional electricity generation complements electricity generation from renewable energies in Europe.

While comparable power plant capacities in Europe are assumed in the scenarios, electricity generation changes, in part substantially, due to other trade flows, depending on the design of the scenario for Germany.

The detailed data on the capacity development of electricity generation plants in the (neighbouring) countries relevant for the modelling is provided in the annex.

5.3 Electricity demand and expansion of renewable energies in Germany

The classification of a phase-out of CO_2-intensive and ultimately all fossil-fired electricity generation and the corresponding development paths over time is dependent, first of all, on the environment of electricity demand:

» The electricity demand trends over the next two decades will be shaped mainly by developments in traditional electricity demand. Substantial effects of more efficient appliances and systems on these trends are likely to arise in the next few years, with the result that gross electricity consumption (without the own consumption of the power plants) amounting to approx. 500 TWh can be expected up to 2030.

» The ambition level of climate policy and the associated demand for new electricity applications (transport, heat, if necessary also power-based energy sources, etc.) are crucial for the development after 2030. In the context of a far-reaching decarbonization of the German economy (which necessarily follows from the available emissions budget), an additional electricity demand will arise from around 2035 onwards and the historical levels of electricity demand will be substantially exceeded in the long term. From 2035 a considerable increase in gross electricity consumption (excluding the own consumption of the power plants) is assumed for the analyses, that leads to levels of up to over 700 TWh for 2050.

» At the same time, different additional electricity demands may arise for the flexibility options (storage losses etc.) from the expansion structures for generation plants based on renewable energies.

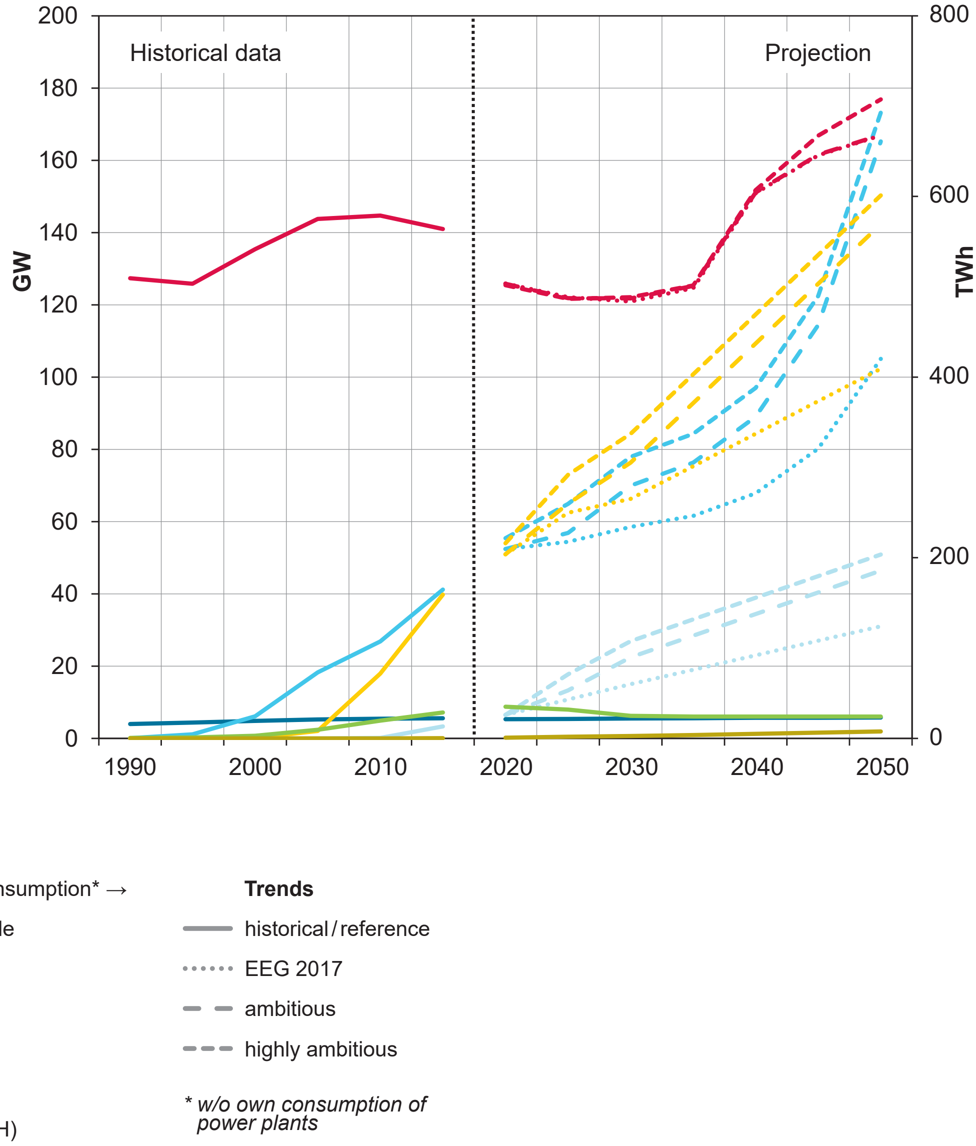
For the present analyses, electricity demands are calculated based on studies with an emission reduction scenario of 95% compared to 1990 levels. Figure 5-6 shows the corresponding gross electricity demand (the own consumption of power plants is excluded).

Against this background, it is already clear that, firstly, an important part of the transition to an electricity system based extensively on renewable energies must be completed by 2035 in order to meet the increasing electricity demand based on renewable energies only. Secondly, it will be necessary to promote the expansion of the capital stock of power generation plants based on renewable energies at an early stage with considerably greater momentum.

The future share of electricity generation based on renewable energies in total electricity generation depends crucially on the speed and rigour at which the capital stock of generation plants based on renewable energies is built up and how quickly or with what lead time the corresponding requirements of grid infrastructures and the necessary flexibility options (demand flexibility, storage, etc.) are created.

Figure 5-6: **Gross electricity demand (without own consumption of power plants) and expansion of renewable electricity generation capacities in Germany, 1990–2050**

Source: Calculations by Öko-Institut



Against this background, three different scenarios are considered in the analysis of the expansion of renewable energies in electricity generation in Germany (Figure 5-6):

1. The first scenario contains an attenuated expansion path for renewable energies in the structure that assumes auction volumes based on the German Renewable Energy Sources Act 2017 (EEG 2017) and has been further developed according to Scenario B 2030 of the approved scenario for the Network Development Plan 2030 (50Hertz et al. 2016a, BNetzA 2016). On this basis the capacities installed in PV plants can slightly and then substantially exceed the capacities installed in onshore wind energy in the coming years. This is mainly the result of the relatively low gross tender volumes for onshore wind power plants combined with the considerably increasing capacity volumes of onshore wind power plants that are being withdrawn from operation due to their age. In 2030, an installed capacity of approx. 66 GW is achieved for PV, approx. 59 GW for onshore wind power and 15 GW for offshore wind power. Up to 2030 the capacity of biomass power plants decreases by approx. a third due to the reduction of their financing via the German EEG. After 2030, the development of PV and offshore wind power is to continue at about the same level; capacity levels of 102 and 31 GW respectively are achieved by 2050. Net onshore wind energy expands considerably again in the course of another repowering cycle, reaching a total capacity of 105 GW by 2050. For biomass, the capacity level remains at an approximately constant level. There are no significant changes in the capacities of other electricity generation plants based on renewable energies.

2. To enable a contrast with this first scenario, another scenario was developed which involves an expansion of electricity generation capacities based on renewable energies up to 2030 that is probably the upper limit of the expansion of the power plant fleet based on renewable energies that can be implemented in real terms, if the currently relatively expensive flexibility options are not to be used right away. For 2030 an installed capacity of onshore wind power plants amounting to 78 GW is achieved, which is approximately double the level of 2015. The PV capacity increases to 84 GW and the capacity of offshore wind power plants amounts to around 33 GW. From 2030 to 2050 these trends are continued with increasing momentum, with the result that onshore and offshore wind power has an installed capacity of 173 and 51 GW and PV a total capacity of 150 GW by 2050.

3. In addition, a scenario was developed which contains an ambitious expansion of renewable energies that does not reach the amounts of the above two scenarios. In principle, the development used was taken (albeit with different emphases for onshore wind power and PV) from scenarios B 2025 and B 2035 of the approved scenario framework for the (no longer used) 2025 Network Development Plan (50Hertz et al. 2016b). By 2030, the installed capacity of onshore wind power increases to approx. 70 GW, offshore wind power plants to above 22 GW and PV to 76 GW. In the two decades after 2030, onshore wind power capacities grow to 165 GW, offshore wind power to 46 GW and solar power to 142 GW.

These three scenarios serve to illustrate the interactions between the phase-out of coal-fired electricity generation and the expansion of electricity generation based on renewable energies. Especially for the time frame after 2030, which is less relevant in this context, other expansion paths for renewable energies development are also conceivable, which will be analyzed in the next phase of this project.

The detailed data on the capacity development of electricity generation plants based on renewable energies as well as on electricity generation is provided in the annex.

6 Scope for solutions: the phase-out of coal in Germany

6.1 Initial considerations

Particularly against the background of the concept of emission budgets, it seems helpful and necessary to define more closely the range of phase-out paths for the use of coal in electricity generation in Germany and thereby also the scope for solutions.

This scope for solutions is determined mainly by three elements:

- What are the technical limits of transforming the overall electricity system that must be taken into account in the shutdown of German coal-fired power plants, at least in quantitative terms?
- What are the boundaries of the instruments for implementing an accelerated phase-out path for coal-fired electricity generation, particularly given that large compensation payments should be avoided (also with a view to the international role model effect)?
- What effects have to be considered when the phase-out path for coal is combined with different ambition levels for the expansion of electricity generation based on renewable energies?

Against this background, two analyses are undertaken using diverse variants, which allow an assessment of the boundaries of action for a phase-out path for coal-fired electricity generation in Germany:

1. A rapid phase-out scenario for the use of coal in Germany's electricity generation, which is geared to the technical limits of a phase-out strategy.
2. Different variants of a scenario in which the regulation-driven shutdown of coal-fired power plants is based on the model for the nuclear phase-out in Germany and founded on the considerations underlying that model.

In the analysis of the two scenarios and the corresponding variants,

- the market-driven interactions with the electricity systems of Germany's neighboring countries are considered;

- measures for guaranteeing the security of supply by (net) firm capacities available to the German market (based on power plants operating in the market and via demand flexibility) at a level of 99 GW are assumed[10];

- it is assumed that the entire portfolio of system services (balancing, reactive power compensation, etc.) is made available across the whole region by the fleet of existing power plants on the side of generation, storage and demand; and

- the final energy demand for electricity and the additional electricity demand arising through the expansion of electricity generation based on renewable energies is met by electricity volumes within the power generation system.

10 An approximate assessment of security of supply is undertaken in each case. The hypothesis used in each case is that a high quality of supply security is guaranteed when total capacities of 99 GW are available from controllable power plant capacity and demand flexibility (maximum load of 84 GW, assuming an average availability of 85% of the power plants relevant to covering peak loads). The question is left open in this analysis as to whether the relevant power plants are made available in Germany or in other countries. At the same time, it should be noted that this is at the conservative end of the assessment given that the contributions to firm capacity made, for example, via the portfolio of the (European) fleet of generating plants based on renewable energies. In this context the model analyses consider the extent to which additional firm capacity would be necessary to guarantee the above-mentioned level of 99 GW. Furthermore, the analysis shows the extent to which these additional capacities are utilized under the framework conditions for load structure and wind and solar availability assumed for each year.

6.2 Estimating the technical limits of phase-out paths for coal

The rapid phase-out scenario for coal-fired electricity generation in Germany, which is based on different dimensions of the technical limits of a phase-out strategy, includes the following assumptions:

1. All coal-fired power plants in Germany are switched off by the beginning of 2025 in the order in which they were put into operation;

2. The most ambitious variant of expanding the use of renewable energies in electricity generation is implemented;

3. The firm capacity needed to guarantee security of supply is provided by power plants in Germany and abroad and corresponding demand flexibility; it is assumed that at least the portion of the measures that make new investments necessary can be implemented by 2025;

4. The necessary measures for power grid infrastructure and, if appropriate, also the natural gas grid infrastructure can be implemented by 2025;

5. The necessary regulatory framework is created so that the measures become effective from the beginning of 2019.

Figure 6-1 shows the corresponding development of electricity generation capacities in power plants with firm capacity[11]:

» From 2015 to 2020, the capacity of power plants operating in the electricity market with firm capacity decreases by 44.4 GW. Of this total 4 GW is attributable to nuclear power plants decommissioned within the scope of the phase-out of nuclear power, approx. 3 GW to lignite-fired power plants decommissioned as part of security standby, and approx. 9 GW to hard coal power plants expected to be unprofitable. In addition, 4.6 GW of natural gas power plant capacity is taken off the market for age and profitability reasons. Due to the measures of the coal phase-out, lignite power plants with a capacity of approx. 12 GW and hard coal-fired power plants with a total capacity of approx. 10 GW are removed from the market. For all other power plants, there are no or at most only marginal changes in the available capacity.

11 All data on power plant capacities, net electricity generation and CO_2 emissions used in the different scenarios is provided in the annex.

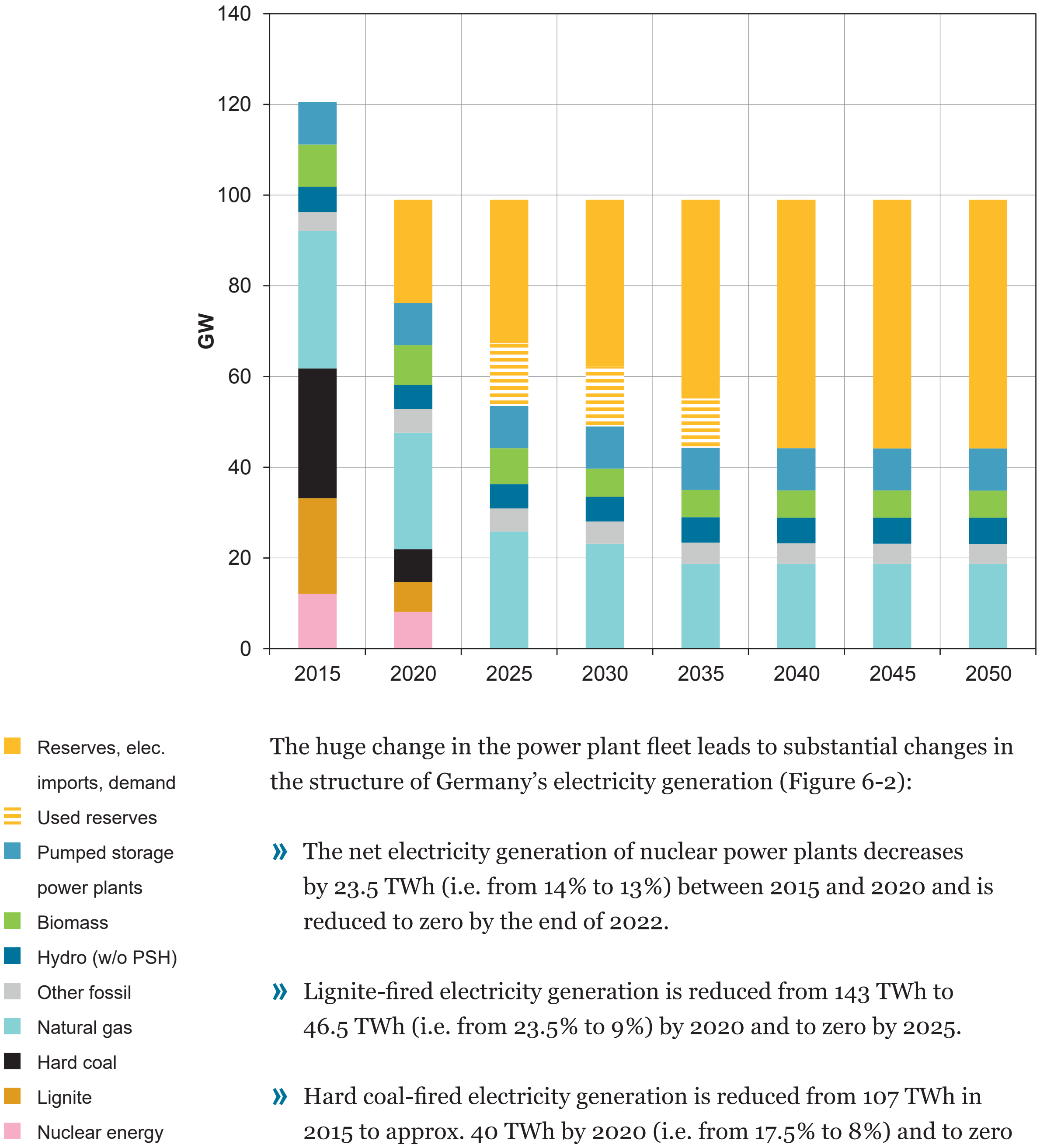
- From 2020 to 2025, the phase-out of nuclear power leads, first of all by the end of 2022, to the shutdown of the remaining nuclear power plant capacities in Germany, which amount to approx. 8 GW. The remaining lignite-fired power plant capacities totaling 6.6 GW and the remaining hard coal-fired power plant capacities totalling approx. 7 GW are taken off the market by the end of 2024. For all other power plants, there are only minor changes in capacity.

- Only the age-related decommissioning of natural gas power plants with a capacity of approx. 7 GW remains for the period after 2025.

- According to the results of the approximate assessment of security of supply, additional power plant capacities of approx. 23 GW for 2020, approx. 45.5 GW for 2025 and 50 to 55 GW from 2030 are needed. These capacities can be provided by putting power plants to be decommissioned into the reserve, demand flexibility, making available power plant capacity from other countries, the construction of new gas turbine plants, portfolio effects of the (European) wind power plant fleet and additional electricity storage. The structure of the corresponding contributions can and will change substantially over the course of time (larger role for reserves and for electricity imports in the short term and an increasing contribution of electricity storage in the medium and long-term). Although this list of possible options shows that a broad and dynamic portfolio of (technical) measures can, in principle, be made available to guarantee a very high level of security of supply, the overall scope of security of supply measures is an important reference level for a comparison with the other scenarios.

Figure 6-1: **Capacity of power plants with firm capacity in the rapid phase-out scenario, 2015–2050**

Source: Calculations by Öko-Institut and Prognos

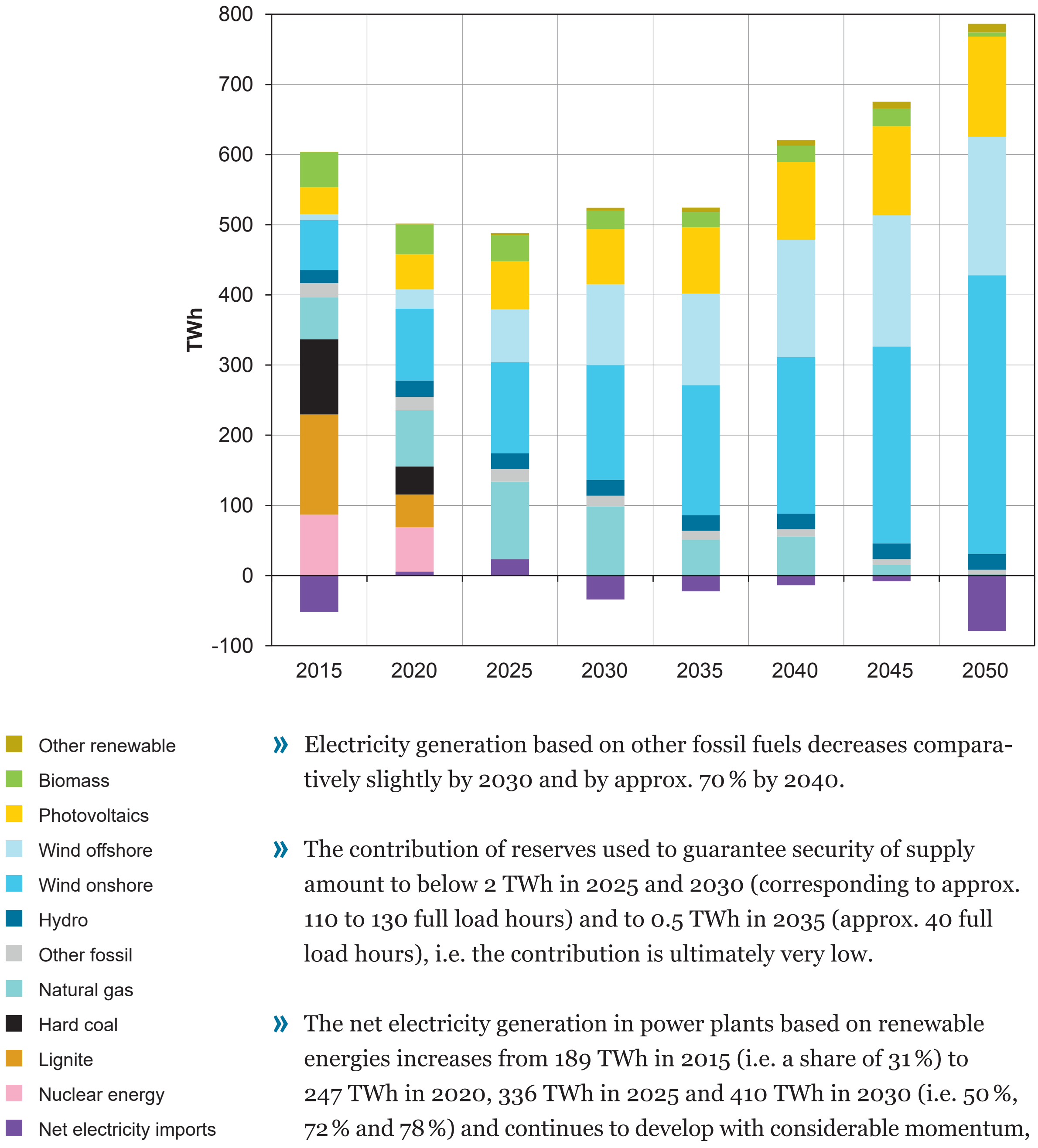


The huge change in the power plant fleet leads to substantial changes in the structure of Germany's electricity generation (Figure 6-2):

- The net electricity generation of nuclear power plants decreases by 23.5 TWh (i.e. from 14% to 13%) between 2015 and 2020 and is reduced to zero by the end of 2022.
- Lignite-fired electricity generation is reduced from 143 TWh to 46.5 TWh (i.e. from 23.5% to 9%) by 2020 and to zero by 2025.
- Hard coal-fired electricity generation is reduced from 107 TWh in 2015 to approx. 40 TWh by 2020 (i.e. from 17.5% to 8%) and to zero by 2025.
- Electricity generation in natural gas-fired power plants increases from approx. 60 TWh in 2015 to 80 TWh in 2020 (i.e. from 10% to 16%) and 110 TWh in 2025 (i.e. to approx. 24%). It decreases slightly between 2025 and 2030 and then substantially after 2030.

Figure 6-2: **Electricity generation in the rapid phase-out scenario, 2015–2050**

Source: Calculations by Öko-Institut and Prognos



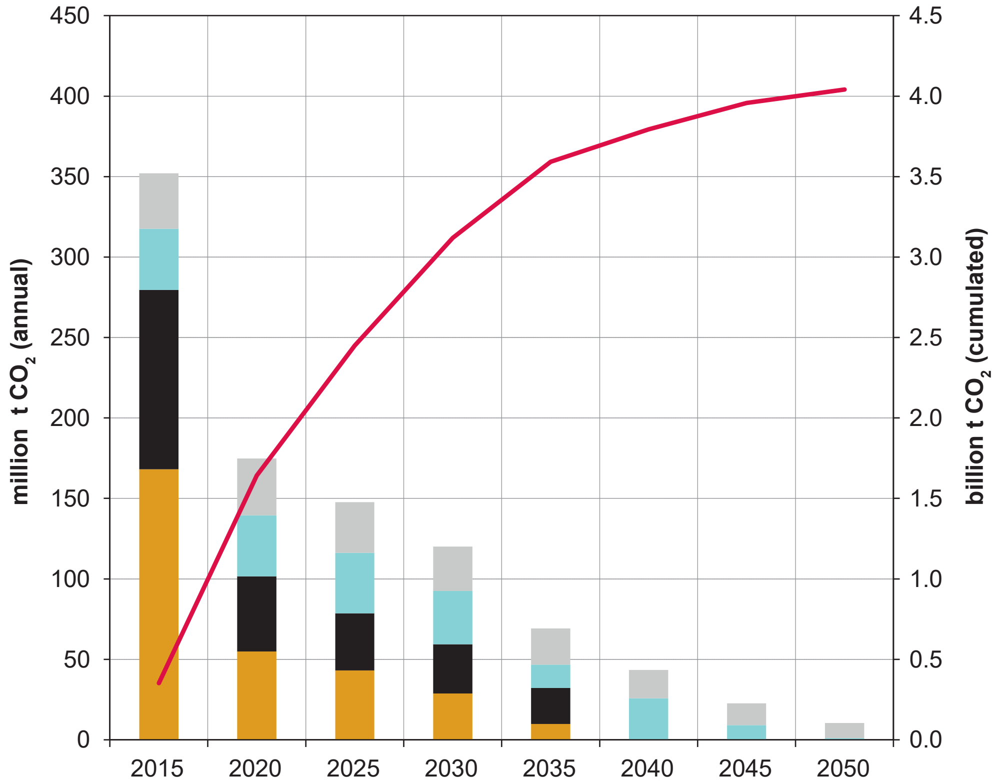
- Electricity generation based on other fossil fuels decreases comparatively slightly by 2030 and by approx. 70 % by 2040.

- The contribution of reserves used to guarantee security of supply amount to below 2 TWh in 2025 and 2030 (corresponding to approx. 110 to 130 full load hours) and to 0.5 TWh in 2035 (approx. 40 full load hours), i.e. the contribution is ultimately very low.

- The net electricity generation in power plants based on renewable energies increases from 189 TWh in 2015 (i.e. a share of 31 %) to 247 TWh in 2020, 336 TWh in 2025 and 410 TWh in 2030 (i.e. 50 %, 72 % and 78 %) and continues to develop with considerable momentum, reaching a level of 778 TWh in 2050 (i.e. a share of 99 %).

Figure 6-3: **Germany's CO_2 emissions in the rapid phase-out scenario, 2015–2050**

Source: Calculations by Öko-Institut and Prognos



Other fossil
Natural gas
Hard coal
Lignite
Cumulative CO_2 emissions

» In terms of the balance of Germany's electricity imports and exports, there is a shift from a significant net export surplus of 52 TWh in 2015 (approx. 8.5% of net electricity generation) to a slight import surplus of 6 TWh in 2020 (approx. 1% of net electricity generation) and a significant import surplus of 24 TWh (approx. 5% of net electricity generation) in 2025. Due to the expansion of renewable energies, surpluses are generated again from 2030 onwards (amounting to between 1% and 10% of total electricity generation), which can either be exported or, especially towards the end of the scenario period, used within the scope of increased sector coupling in Germany.

Correspondingly, the CO_2 emissions of electricity generation in Germany (Figure 6-3) decrease from 352 million t CO_2 in 2015 to 153 million t CO_2 in 2020, 83 million t CO_2 in 2025 and 72 million t in 2030. After this, they steadily decrease to approx. 10 million t CO_2 at the end of the scenario period.

In view of the (net) surplus electricity imports that sometimes arise, the additional CO_2 emissions arising in the other countries need to be taken into account; they amount to 2 million t CO_2 in 2020 and 12 million t CO_2 in 2025. Germany's total balance of CO_2 emission reductions thereby changes only marginally, even when the scope of the emission balance transcends its geographical borders.

From 2015, cumulative emissions increase (without taking into account the effects of the other countries) to 1.62 billion t CO_2 by 2020 and 2.2 and 2.6 billion t CO_2 by 2025 and 2030 respectively. Cumulative CO_2 emissions of approx. 3.3 billion tonnes arise by 2050. Of the cumulative CO_2 emissions from 2015 to 2030, 32% is attributable to lignite, 22% to hard coal and 26% to natural gas electricity generation. By 2050, the shares amount to 25% for lignite, 17% for hard coal, 31.5% for natural gas and 27% for other fossil fuels.

From the perspective of emission reductions, the development shown in this scenario can substantially underuse the emissions budget derived in chapter 4 for German power generation, amounting to 4.0 to 4.2 billion t CO_2. With such a development path, challenges arise mainly as a result of the necessary (technical) short-term measures to guarantee security of supply while electricity generation based on renewable energies does not yet have the same expansion momentum as the huge reduction in fossil-fired electricity generation.

6.3 Estimating the boundaries of legal measures

In contrast to the rapid phase-out scenario, which (under decidedly ambitious assumptions) considers the technical limits of a very rapid abandonment of coal-fired power generation and largely ignores the legal feasibility of such a path, other variants of phase-out paths for the phase-out of coal-fired electricity generation in Germany that are based on legal measures are shown in a further step of the analysis. The starting point for these model analyses is the implementation of the nuclear phase-out that was negotiated in Germany in 2000. It was assumed that the phase-out of nuclear power generation should be implemented without compensation payments being made. The model ultimately negotiated was based on the agreement that the power plants concerned have a standard lifetime of 32 years (BReg 2001), though significantly lower lifetimes of 18 to 25 years were discussed prior to this (WI and Öko-Institut 2000).

Taking into account the fact that the production costs of coal-fired power plants have a higher share of variable operating costs than nuclear power plants but also that the heterogeneity of coal-fired power plants in Germany is substantially larger than that of the nuclear power plants subject to phase-out, the analyses took as a basis three different variants of limiting plant lifetimes to the following (from the start of commercial operation):

» 20 years

» 25 years

» 30 years

The scenario that assumes plant lifetimes of 30 years would thus be roughly identical to the economic considerations behind the decision of Germany’s phase-out of nuclear power (BReg 2001) and the scenario with 20-year plant lifetimes to the ambitious margins of the debate at that time (WI and Öko-Institut). Limiting the lifetimes of coal-fired power plants to 25 years constitutes a middle scenario.

Against the background of the considerable importance given to the momentum of expanding the use of renewable energies in electricity generation by classifying the emissions of different coal phase-out paths, the different scenarios for limiting the lifetimes of lignite and hard coal-fired power plants are combined with the following two variants of the expansion of renewable energies (Chapter 5.3):

» The expansion is based on the German Renewable Energy Sources Act 2017 (EEG) and the scenario frameworks for the 2030 Network Development Plan; and

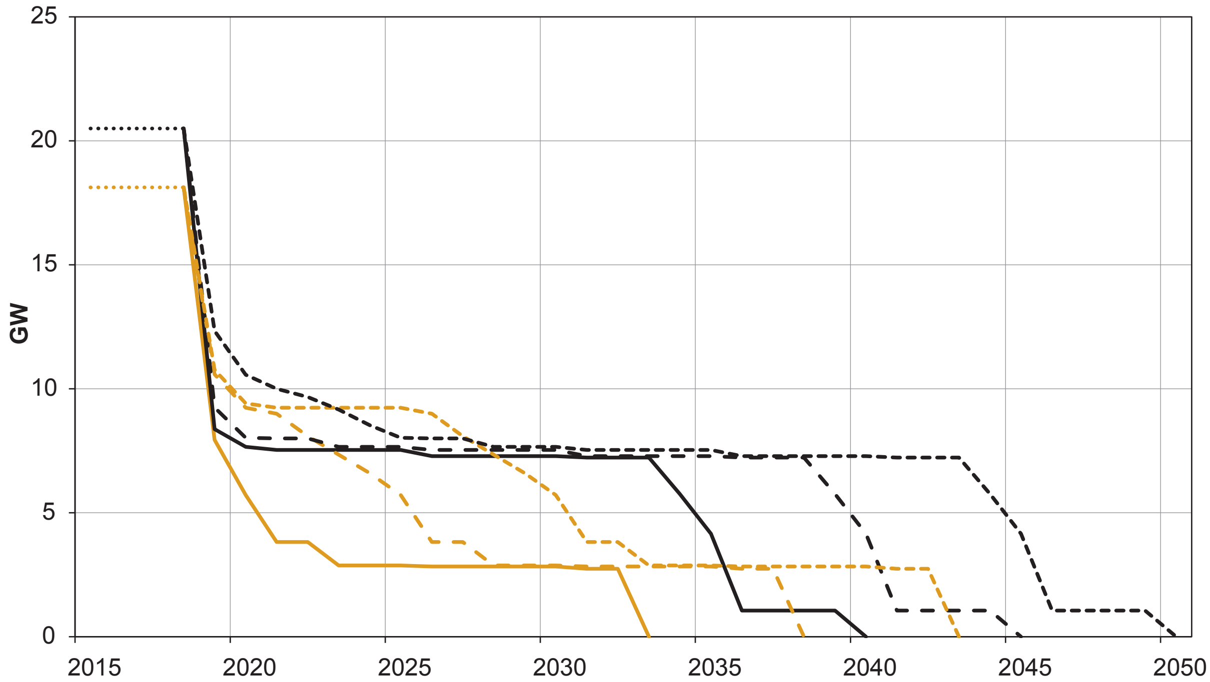
» An ambitious expansion, which does not completely exhaust the limits of technical feasibility and is based on the 2025 Network Development Plan.

Furthermore, it was assumed that the necessary grid infrastructure for electricity and natural gas supply up to 2025 and 2035 can be adapted to the changed technical and geographical structures of the electricity system, also when procedural and regulatory lead times are taken into account.

It was also assumed that the regulatory framework for the accelerated phase-out of coal-fired electricity generation in Germany can be created rapidly enough to enable the relevant regulations to become effective at the beginning of 2019.

Figure 6-4: **Firm capacity of lignite and hard coal power plants in plant lifetime scenarios, 2015–2050**

Source: Calculations by Öko-Institut and Prognos



The following development results for lignite and hard coal power plants operated in the electricity market (Figure 6-4):

» From 2015 to 2020, the capacity of lignite power plants in the variants with a guaranteed minimum operating life of 20, 25 and 30 years is reduced by 15 (maximum lifetime of 20 years) and 12 GW (maximum lifetimes of 25 and 30 years); approx. 9 GW is attributable to power plants that are to beshut down anyway for profitability reasons. For the rest of the power plant fleet, there are only minor changes compared to the developments described in chapter 6.2.

» From 2020 to 2025 there is an additional removal of 3 and 3.5 GW of lignite power plant capacity for plants with a guaranteed operating life of 20 and 25 years respectively; for power plants with a maximum 30-year lifetime, there is no further shutdown of significant capacities during this period. The capacity of hard coal-fired power plants is reduced by 2.5 GW only in the scenario with maximum plant lifetimes of 30 years; in the other two scenarios only minor changes in capacity result.

» From 2025 to 2030, a lignite-based power plant capacity of approx. 3 GW is removed from the market in the scenario with a plant lifetime of 25 years and 3.5 GW in the 30-year plant lifetime scenario. In terms of hard coal-fired power plants, only small decreases in capacity occur during these years.

» From 2030 to 2035 lignite power plants with a capacity of approx. 3 GW are taken off the market in both scenarios with maximum plant lifetimes of 20 and 30 years. For the scenario with a maximum plant lifetime of 25 years, there are no changes during this period. For hard coal-fired power plants, significant capacity reductions amounting to 3 GW result only in the scenario with a 25-year plant lifetime.

» From 2035 to 2040 the last lignite power plants with a total capacity of approx. 3 GW are removed from the market in the variant with a maximum plant lifetime of 25 years. For longer maximum lifetimes there are no changes. In terms of the hard coal-fired power plants, capacities of 4 and 2 GW are shut down for the variants with maximum lifetimes of 20 and 25 years respectively.

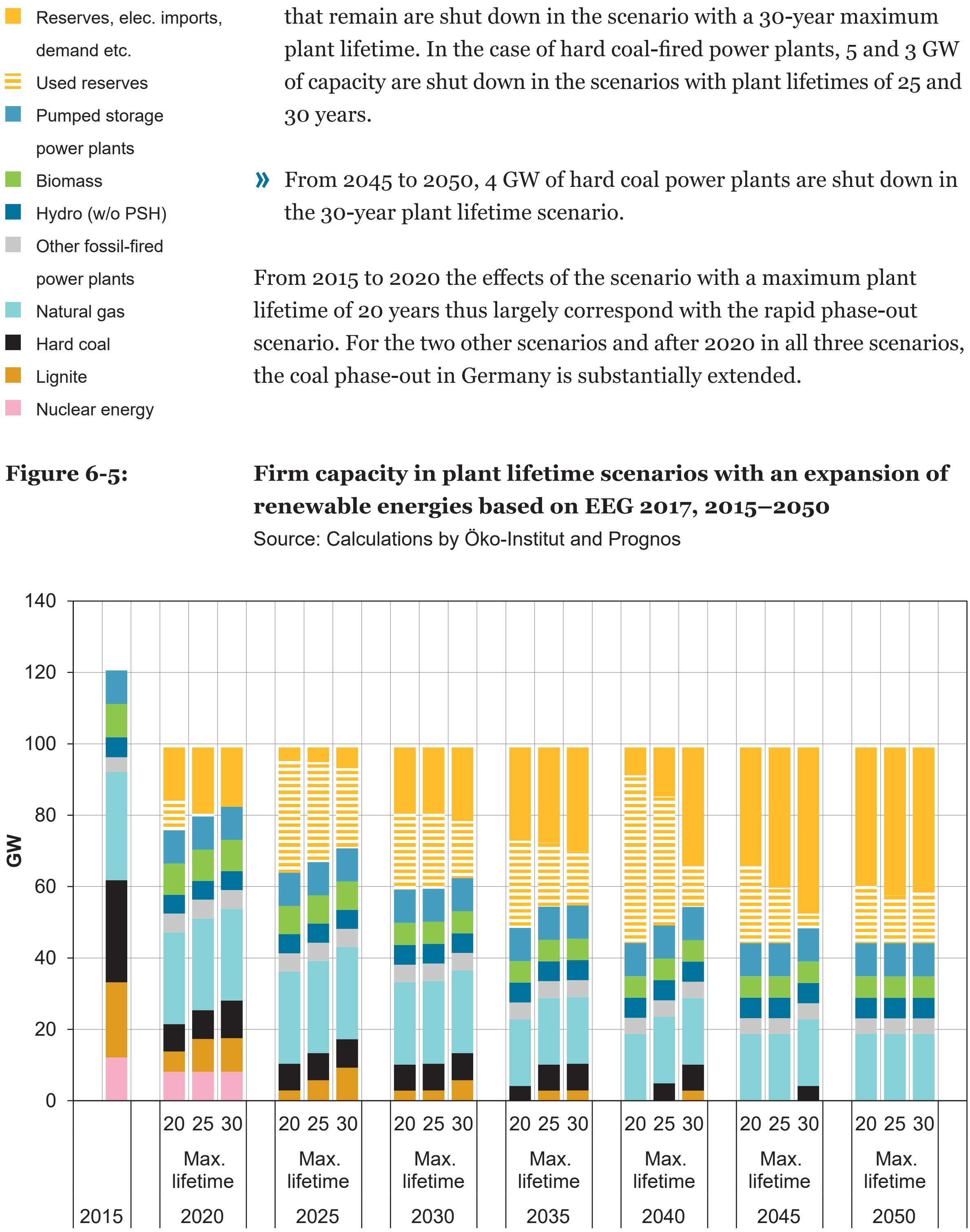
» From 2040 to 2045, the approx. 3 GW of lignite power plant capacity that remain are shut down in the scenario with a 30-year maximum plant lifetime. In the case of hard coal-fired power plants, 5 and 3 GW of capacity are shut down in the scenarios with plant lifetimes of 25 and 30 years.

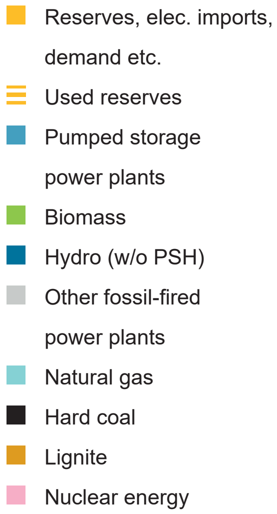
» From 2045 to 2050, 4 GW of hard coal power plants are shut down in the 30-year plant lifetime scenario.

From 2015 to 2020 the effects of the scenario with a maximum plant lifetime of 20 years thus largely correspond with the rapid phase-out scenario. For the two other scenarios and after 2020 in all three scenarios, the coal phase-out in Germany is substantially extended.

Figure 6-5: **Firm capacity in plant lifetime scenarios with an expansion of renewable energies based on EEG 2017, 2015–2050**

Source: Calculations by Öko-Institut and Prognos





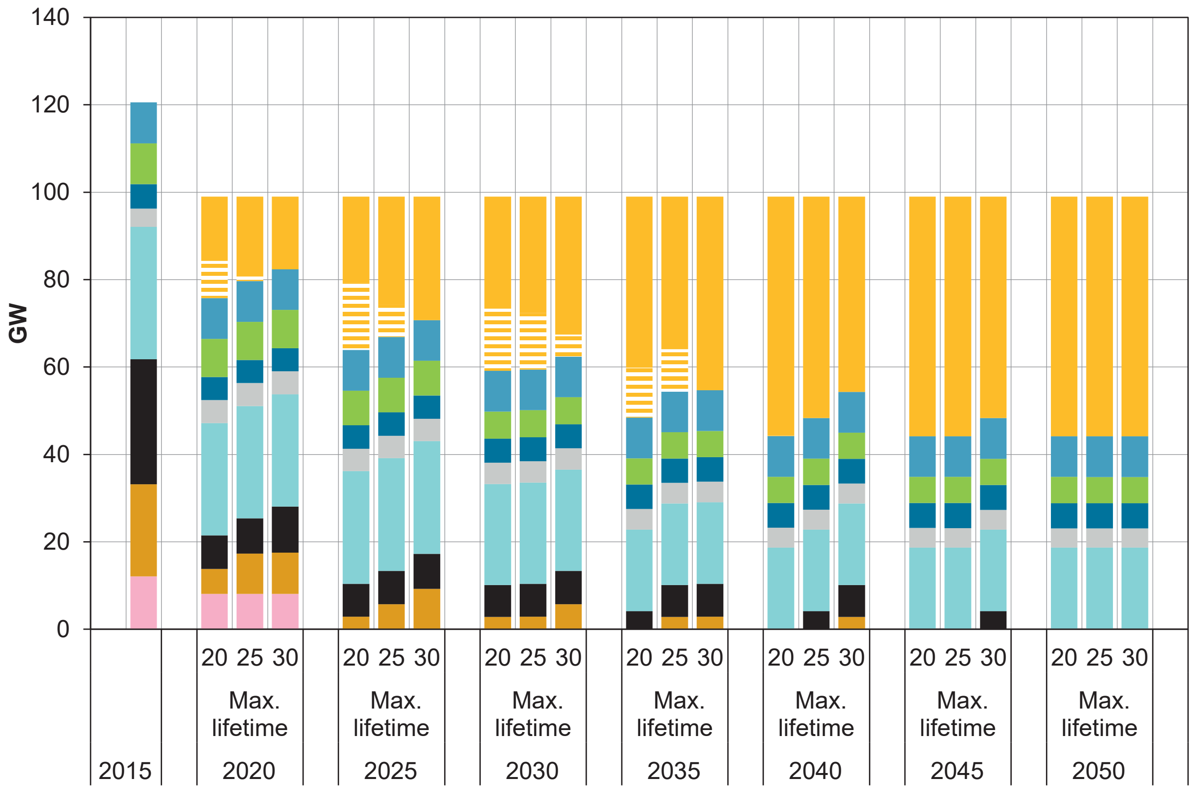
With a view to the capacities needed to guarantee security of supply in Germany, the following situation results:

- From 2015 to 2020, the additional capacities needed for the 20-year plant lifetime scenario amount to approx. the level determined for the rapid phase-out scenario (23 GW). For the two other scenarios (maximum lifetime of 25 and 30 years), this level is lower, by approx. 4 GW and 7 GW respectively.

- From 2020 to 2025, the capacity needed to guarantee security of supply is 10 GW lower in the scenario with a 20-year plant lifetime than in the rapid phase-out. In the other scenarios, the capacity levels needed are 3 and 7 GW lower (for maximum plant lifetimes of 25 and 30 years respectively).

Figure 6-6: **Firm capacity in plant lifetime scenarios with an ambitious expansion of renewable energies, 2015–2050**

Source: Calculations by Öko-Institut and Prognos



- From 2025 to 2030, the capacity needed to guarantee security of supply is 10 GW lower for the scenarios with 20 and 25-year plant lifetimes than in the rapid phase-out scenario. For the scenario with a maximum plant lifetime of 30 years the level is approx. 3 GW lower.

- From 2030 to 2035, the additional capacity needed to guarantee security of supply in the plant lifetime scenario for 20 years is about 4 GW below that of the rapid phase-out scenario; in the other two scenarios, it is approx. 6 GW below this level.

- From 2035 to 2040, the difference in capacity needed to guarantee security of supply between the rapid phase-out scenario and the scenario with a 20-year plant lifetime decreases to nearly zero. For the two other scenarios the levels are approx. 5 and 10 GW lower (maximum plant lifetimes of 25 and 30 years respectively).

- From 2040 to 2045, the additional capacity needed to guarantee security of supply in the two scenarios with 20 and 25-year plant lifetimes and in the rapid phase-out scenario converge; only in the scenario with a plant lifetime of 30 years is the level 4 GW lower.

- From 2045 to 2050, the additional capacity needed to guarantee security of supply – that is met via reserves, electricity imports from other countries, demand flexibility, the wind power portfolio and electricity storage – amounts to 55 GW for all scenarios.

The modelling results for the plant lifetime scenarios show that the additional capacity needed to guarantee security of supply in the German electricity system is lower than in the rapid phase-out scenario, by up to 7 GW for 2020, up to 17 GW for 2025, up to 13 GW for 2030, up to 10 GW for 2035 and 2040 and up to 4 GW for 2045. However, especially with a view to 2020, the additional capacity of at least 17 GW needed to guarantee security of supply remains quite ambitious, although by no means illusionary considering the transfer of natural gas and hard coal-fired power plants to interim reserves, electricity imports available from other countries, the (European) wind power portfolio and the (limited) construction of gas turbine or similar power plants.

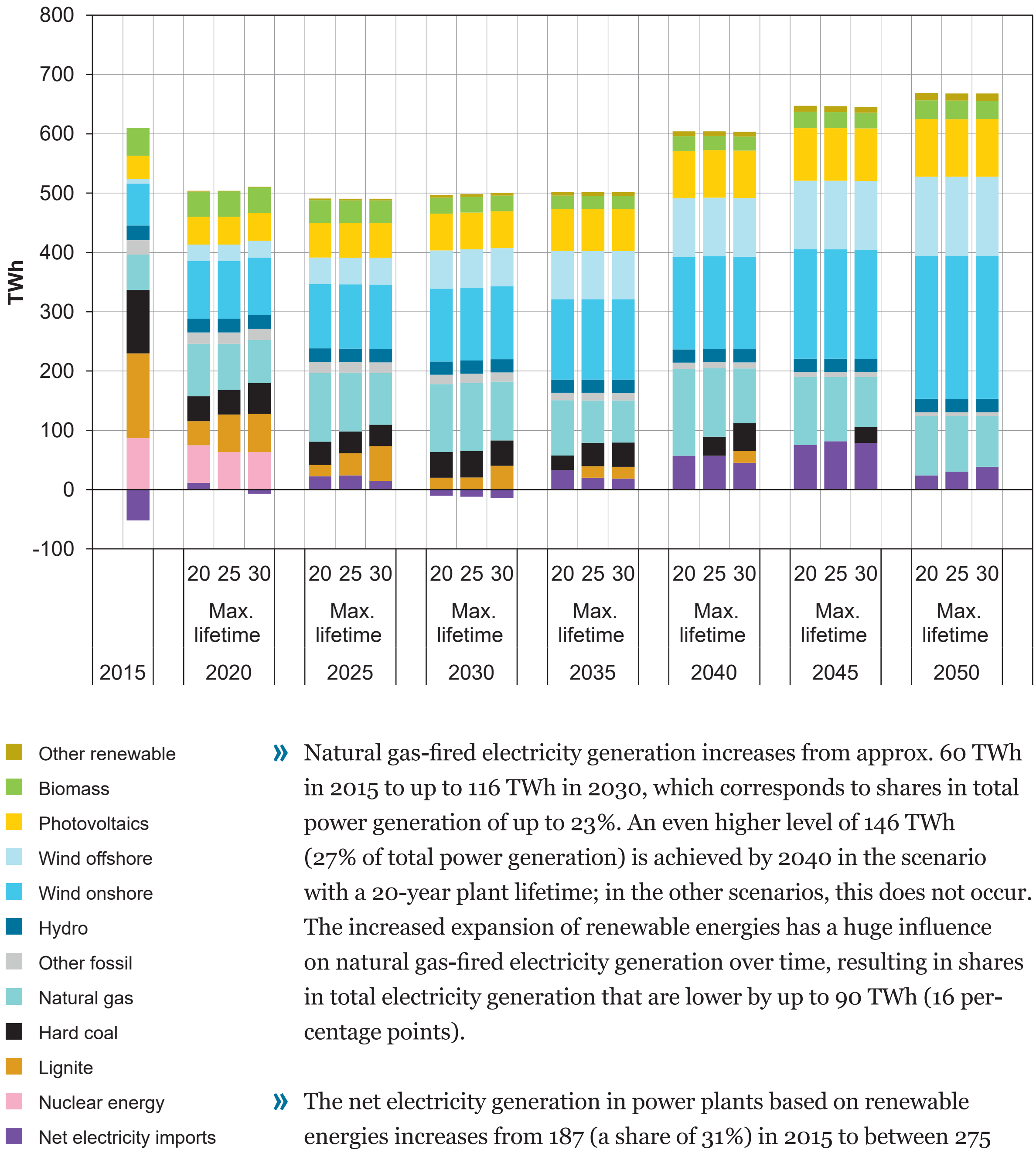
» The changes in the fossil and renewable shares of Germany's power plant fleet are also reflected in the substantial changes in Germany's electricity generation (Figure 6-6 and Figure 6-7):

» The production of lignite-fired power plants decreases from 143 TWh in 2015 to between 41 and 65 TWh in 2020, which corresponds to shares in the total electricity generation of 8% to 13%. For 2025, a range of 19 to 59 TWh (i.e. shares in electricity generation of 4% to 12%) is achieved, if the expansion path assumed for renewable electricity generation is based on EEG 2017. For 2030, a range of 20 to 40 TWh and shares in the total electricity generation of 4% to 8% result. In 2035 about 20 TWh of electricity (4% of total electricity generation) is produced from lignite only in the variants with plant lifetimes of 25 and 30 years. In 2040 only a small portion of lignite-fired electricity generation remains (20 TWh, corresponding to approx. 4% of total electricity generation) only in the scenario which assumes plant lifetimes of 30 years; after this, the share of lignite production in Germany's total electricity generation is reduced to zero. Variating the expansion path for renewable electricity generation only has a minor impact on the level of lignite-fired electricity generation.

» Hard coal-fired electricity generation decreases from 107 TWh in 2015 to between 42 and 52 TWh in 2020, i.e. from a share in electricity generation of 17.5% to between 8.5% and 10%. For 2025 a relatively narrow range of 36 to 39 TWh and a production share of approx. 8% result. This situation continues for 2030 (production of 43 to 45 TWh and shares of approx. 9%). Only for 2035 do significant differences arise again for the different plant lifetime scenarios; these range from 25 to 41 TWh and 5% to 8.5%. In 2040 hard coal-fired power plants only contribute to electricity generation for the 25 and 30-year plant life-time scenarios; the corresponding levels remain low, however, at 32 to 46 TWh and shares in total electricity generation of 6% to 8%. Only the scenario assuming 30-year plant lifetimes contains hard coal-fired electricity generation in 2045 (27 TWh corresponding to 5%) before such production is completely abandoned in Germany by 2050. In contrast to electricity generation from lignite, an increased expansion of renewable energies has an important impact on the level of hard coal-fired electricity generation, particularly from 2030 to 2045 when hard coal-fired levels of electricity generation are lower by up to 14 TWh and the shares in total electricity generation are lower by up to 3 percentage points.

Figure 6-7: **Electricity generation in plant lifetime scenarios with an expansion of renewable energies based on EEG 2017, 2015–2050**

Source: Calculations by Öko-Institut and Prognos

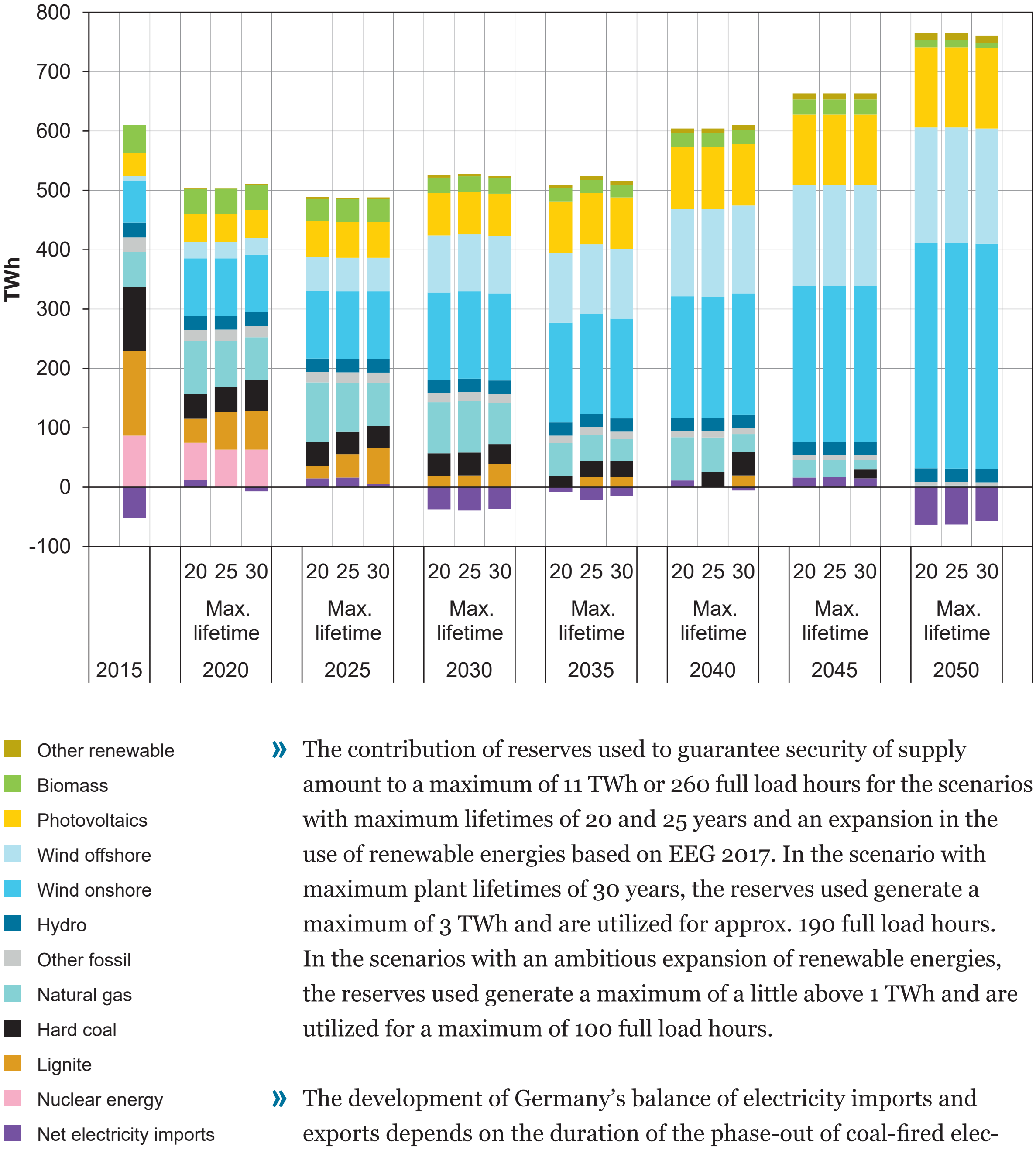


» Natural gas-fired electricity generation increases from approx. 60 TWh in 2015 to up to 116 TWh in 2030, which corresponds to shares in total power generation of up to 23%. An even higher level of 146 TWh (27% of total power generation) is achieved by 2040 in the scenario with a 20-year plant lifetime; in the other scenarios, this does not occur. The increased expansion of renewable energies has a huge influence on natural gas-fired electricity generation over time, resulting in shares in total electricity generation that are lower by up to 90 TWh (16 percentage points).

» The net electricity generation in power plants based on renewable energies increases from 187 (a share of 31%) in 2015 to between 275 and 295 TWh in 2025 (depending on the expansion path) and shares in total power generation of between 58% and 62%. From 2025 to 2050, these levels range from approx. 540 TWh and 85% (expansion based on EEG 2017) to approx. 755 TWh and 99% (scenario with ambitious expansion).

Figure 6-8: **Electricity generation in plant lifetime scenarios with an ambitious expansion of renewable energies, 2015–2050**

Source: Calculations by Öko-Institut and Prognos

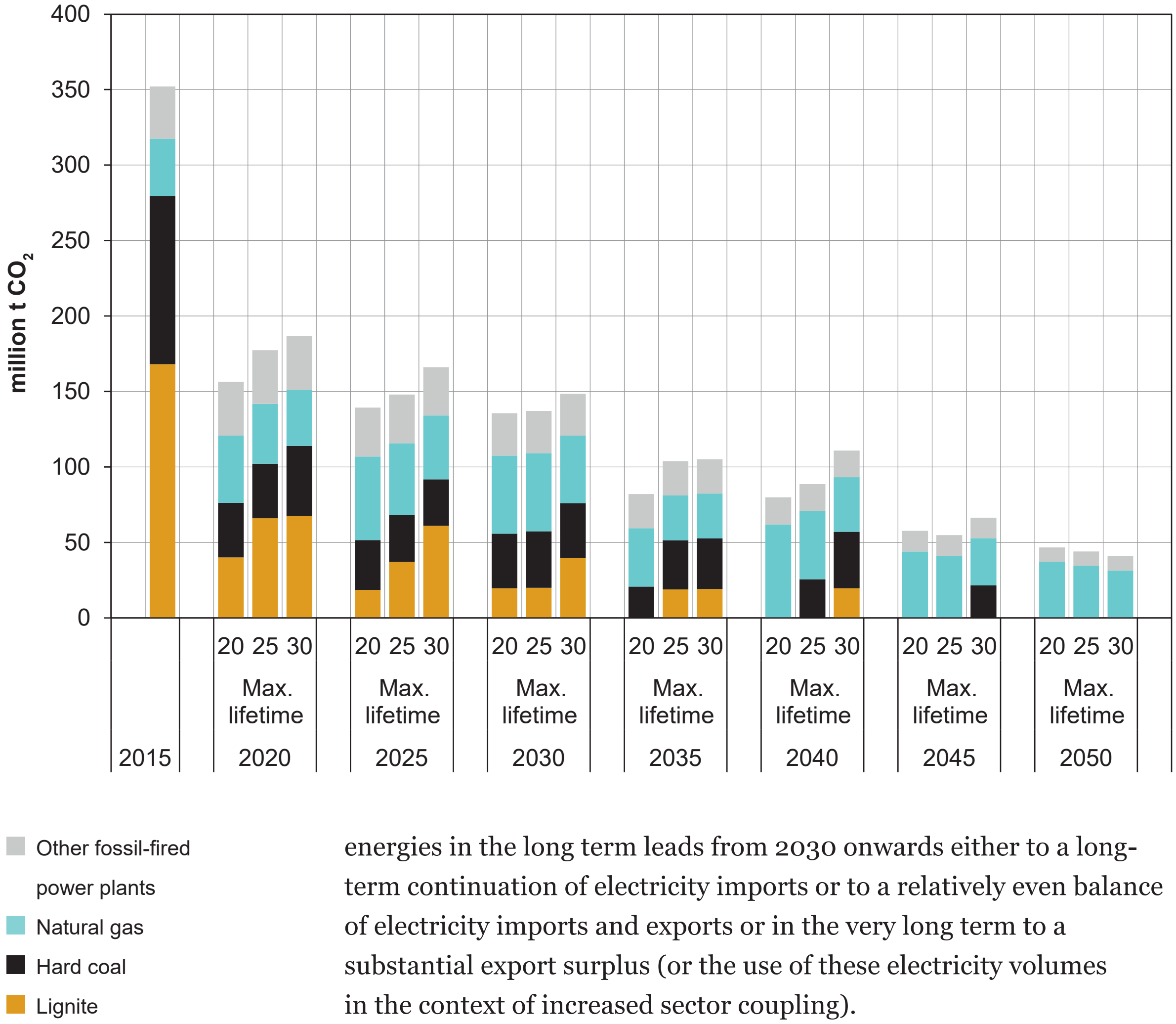


» The contribution of reserves used to guarantee security of supply amount to a maximum of 11 TWh or 260 full load hours for the scenarios with maximum lifetimes of 20 and 25 years and an expansion in the use of renewable energies based on EEG 2017. In the scenario with maximum plant lifetimes of 30 years, the reserves used generate a maximum of 3 TWh and are utilized for approx. 190 full load hours. In the scenarios with an ambitious expansion of renewable energies, the reserves used generate a maximum of a little above 1 TWh and are utilized for a maximum of 100 full load hours.

» The development of Germany's balance of electricity imports and exports depends on the duration of the phase-out of coal-fired electricity generation and, much more heavily, on the ambition level of the expansion in the use of renewable energies in electricity generation. The scenarios with plant lifetimes of 20 and 25 years in particular result in (above all for 2025) slight net surplus imports amounting to 15 to 24 TWh, which decrease again extensively by 2030. The more or less ambitious expansion of electricity generation based on renewable

Figure 6-9: **CO_2 emissions in plant lifetime scenarios with an expansion of renewable energies based on EEG 2017, 2015–2050**

Source: Calculations by Öko-Institut and Prognos



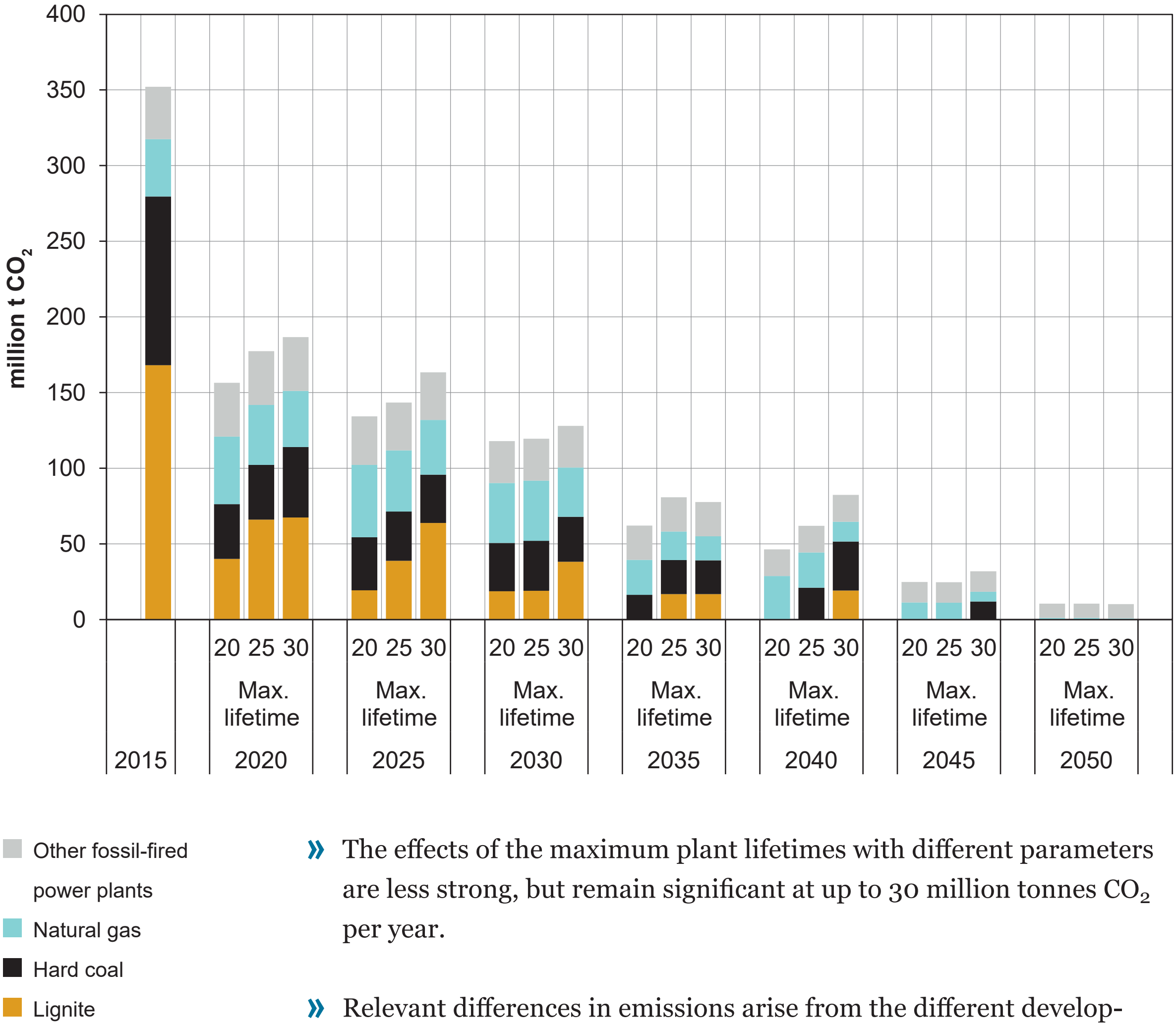
energies in the long term leads from 2030 onwards either to a long-term continuation of electricity imports or to a relatively even balance of electricity imports and exports or in the very long term to a substantial export surplus (or the use of these electricity volumes in the context of increased sector coupling).

Analogous to the development of electricity generation and cross-border electricity flows, the developments of CO_2 emissions for Germany's domestic balance are shown in Figure 6-9 and Figure 6-10. Three different patterns can be identified above all:

» The emission reductions achieved by 2020 and 2025 are particularly strong in all scenarios considered here and range from 166 to 218 million tonnes of CO_2 (47% to 60% compared to 2015). This is essentially an effect of the large and very old coal-fired power plant fleet in Germany, the production of which is curtailed very quickly by the maximum plant lifetimes.

Figure 6-10: **CO_2 emissions in plant lifetime scenarios with an ambitious expansion of renewable energies, 2015–2050**

Source: Calculations by Öko-Institut and Prognos



» The effects of the maximum plant lifetimes with different parameters are less strong, but remain significant at up to 30 million tonnes CO_2 per year.

» Relevant differences in emissions arise from the different development expansion paths for renewable energies, particularly in the long term. In view of the slow development of the related capital stock, the scenario with the most ambitious expansion in the use of renewable energies in electricity generation leads to significant differences in CO_2 emissions compared to the scenario based on the German EEG 2017 (17 to 27 million tonnes CO_2 per year), which then increase considerably over the course of time and reach 31 to 36 million tonnes CO_2 per year in 2050.

As a result of the net electricity imports for the scenario with a maximum plant lifetime of 20 years, Germany generates additional emissions of approx. 4 million tonnes CO_2 abroad by 2020. For 2025, CO_2 emissions outside of the geographical scope of Germany's balance increase by 9 to

11 million tonnes CO_2 for most of the plant lifetime scenarios. For the combination of a plant lifetime limit of 30 years with the most ambitious expansion of renewable electricity generation, CO_2 emissions amount to only approx. 2 million tonnes.

In the longer term (i.e. from 2035 onwards), net electricity imports in the scenarios with an expansion of renewable electricity generation based on EEG 2017 give rise, in other countries, to additional CO_2 emissions of 10 to 13 million t CO_2 (2035) and 19 to 24 million t CO_2 (2040). In the scenarios with an ambitious expansion of renewable energies in Germany, there are either no additional CO_2 emissions or even (slight) beneficial effects on emission levels in 2035 and 2040. From an overall perspective, therefore, there are no significant changes in the classification of the achievable emission reduction effects of the different phase-out paths for coal. Furthermore, the large significance of an ambitious expansion of electricity generation based on renewable energies is again evident when the scope of the emission balance is expanded to include Germany's (electricity) neighbouring countries.

The cumulative CO_2 emissions from 2015 to 2050 amount to approx. 4.6 billion tonnes in the 20-year plant lifetime scenario, 4.9 billion tonnes in the 25-year plant lifetime scenario and 5.25 billion tonnes in the 30-year plant lifetime scenario. The (rapid) transition to an ambitious expansion scenario for renewable energies reduces each of these levels by approx. 600 million t CO_2.

6.4 Interim conclusions

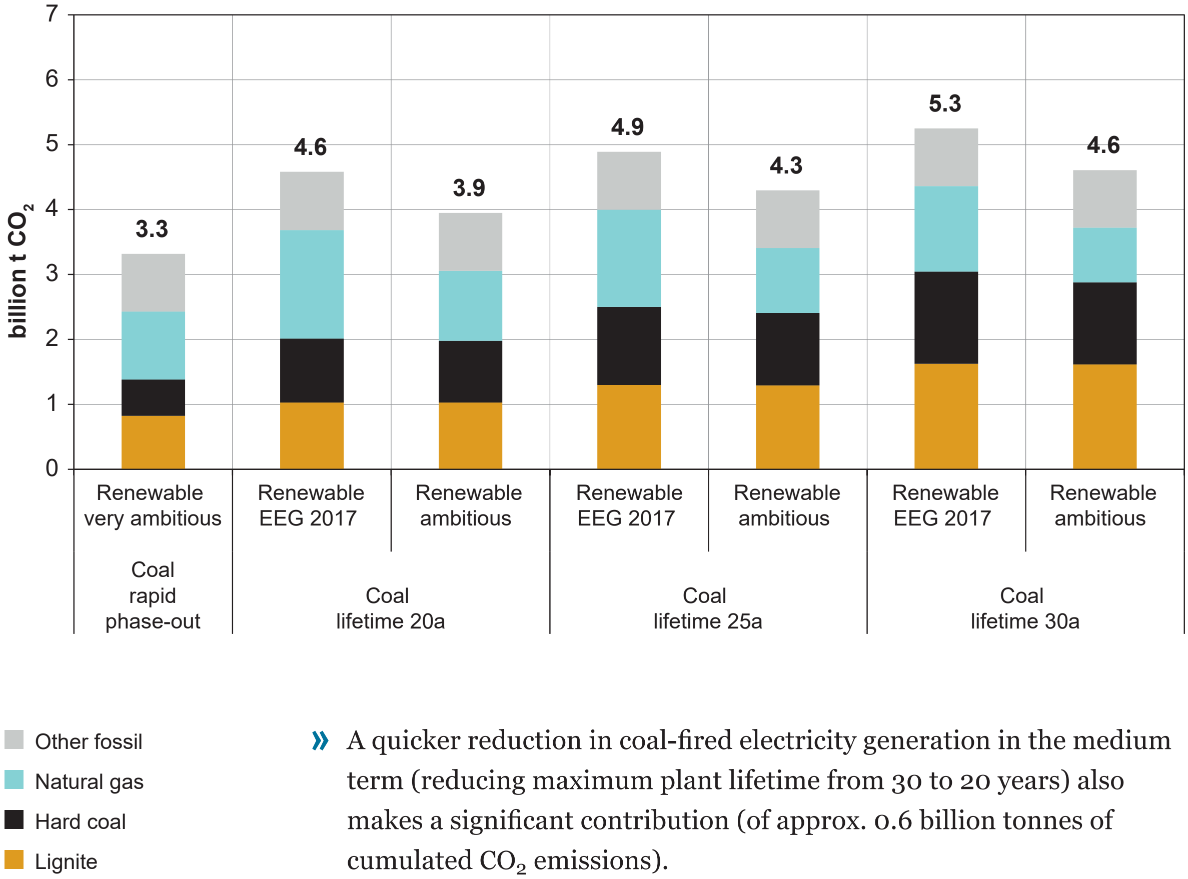
The analysis conducted on the scope for solutions regarding the phase-out path of coal-fired electricity generation in Germany shows the areas that are crucial to climate policy decision-making for a sector which has a high proportion of very old power plants that all have very high emission levels.

These fields of tension relate firstly to keeping within the emission budget from 2015 to 2050 (Figure 6-11):

» It is only possible to remain within certain emission budgets (distributed on a fair share basis), if significant emission reductions can be realized relatively quickly. Even if only the technical limits are considered (with very ambitious assumptions), use of at least 3.3 billion tonnes of the carbon budget remains.

Figure 6-11: **Cumulative CO_2 emissions in rapid phase-out and plant lifetime scenarios, 2015–2050**

Source: Calculations by Öko-Institut and Prognos



- A quicker reduction in coal-fired electricity generation in the medium term (reducing maximum plant lifetime from 30 to 20 years) also makes a significant contribution (of approx. 0.6 billion tonnes of cumulated CO_2 emissions).

- If sufficient generation capacities based on renewable energies cannot be created in the medium and long-term, natural gas-fired electricity generation creates a long-term emission base (amounting to approx. 0.6 billion tonnes of cumulated CO_2 emissions).

In the final analysis, the overview of the modelling results on Germany's cumulative CO_2 emissions shows that

- only the rapid phase-out scenario combined with a very ambitious expansion of renewable electricity generation, or

- substantial limits on the plant lifetimes of coal-fired power plants combined with an ambitious expansion of renewable energies

leads to cumulative emissions of 4.0 to 4.2 billion tonnes of CO_2 from 2015 to 2050, which are still (somewhat) compatible with the emissions budget determined for the German electricity sector.

The overall modelling results also make clear that a phase-out strategy for coal-fired electricity generation in a Germany that is geared purely to taking power plant capacities out of operation, only remains within the emissions budget when very considerable limits are introduced on plant lifetimes in the short term and when the expansion of renewable energies is hugely accelerated in the long term. However, the implications of this and the (ambitious) demands of such strategies make it advisable to consider expanding the mechanisms for a climate-fair phase-out of coal-fired electricity generation in Germany and not to focus exclusively on capacity management mechanisms.

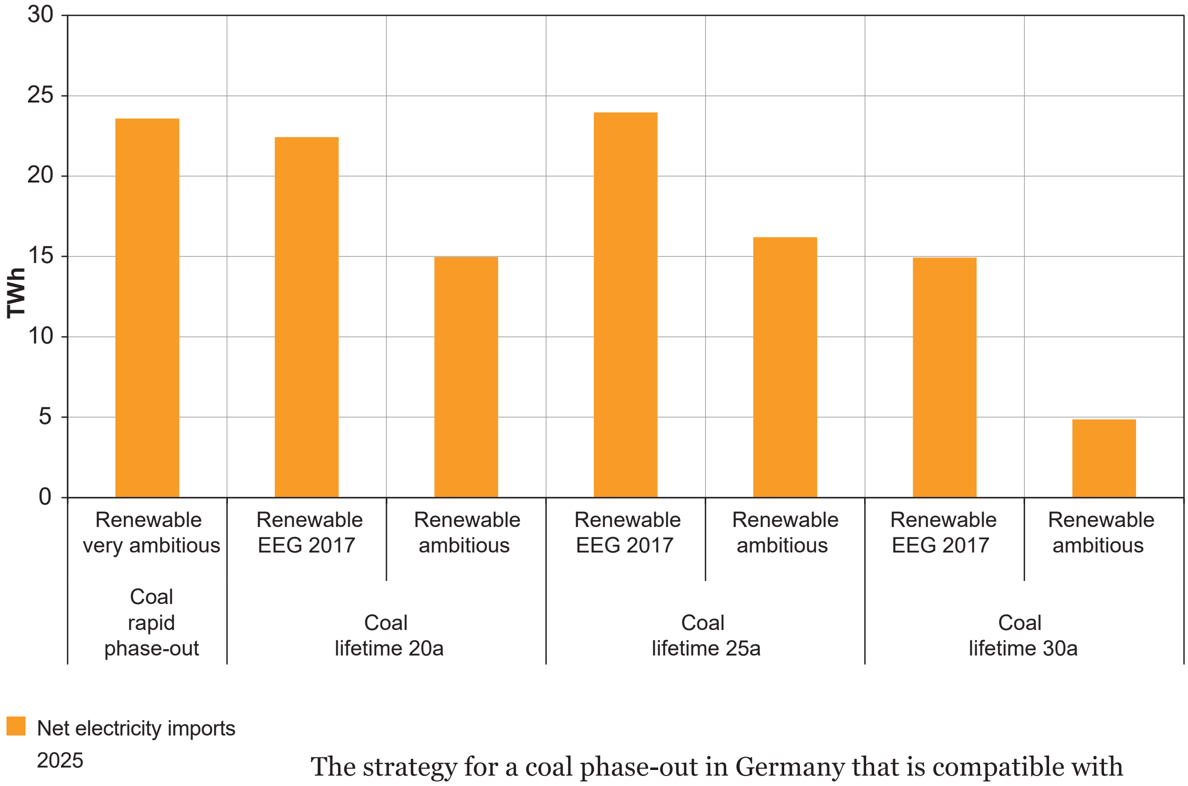
At the same time, the challenges arising from the energy-economic implications and the effects on the system of the integrated European electricity market also have to be taken into account, especially with a view to the CO_2 emissions that Germany hereby generates in other countries in Europe

- The quick decommissioning of very large coal-fired power plant capacities can entail substantial challenges for cross-regional security of supply. In a very short period of time, alternative options for covering all conceivable load and production constellations have to be tapped, both in Germany and in other countries on the demand and supply side. While this is conceivable as a model, its practical implementation would likely involve risks, particularly with regard to the speed with which appropriate regulation can be introduced and the necessary speed with which the market actors would have to adapt.

- The slowness in replacing coal-fired electricity generation with plants based on renewable energies arising from the time needed to expand such capacities (project lead times, creation of necessary infrastructures, etc.) and the technical and economic limits of substantially expanding natural gas-fired electricity generation can lead to a considerable increase in net electricity imports in the short term. In turn this can lead to additional CO_2 emissions in other countries (Figure 6-12), which can range from 2 to 12 million t CO_2 for 2025 but which have only a secondary importance in the classification of the total emission reduction effects.

Figure 6-12: **Net electricity imports in rapid coal phase-out and plant lifetime scenarios, 2025**

Source: Calculations by Öko-Institut and Prognos



The strategy for a coal phase-out in Germany that is compatible with the emissions budget, which constitutes sound climate policy from the cross-border perspective and is robust in terms of guaranteeing security of supply will have to be based on models that are more complex than the ideal cases shown here. The analyses have also shown that the timely initiation of an ambitious expansion of electricity generation capacities based on renewable energies is also a key factor for keeping emissions within the emission budget.

7 A phase-out path for coal in Germany

7.1 Design and effects on the electricity system

Against the background of the analysis provided in Chapter 6 on the scope for solutions geared to carbon budgets, the following model was used:

- Coal-fired electricity generation is phased out by the end of 2035, i.e. before there is substantial growth again in electricity demand due to the increasing importance of sectoral coupling. Almost all power plants operated in Germany can thus be operated without additional restrictions for a period of 20 years. The only exception is the power plant Datteln IV, for which a specific solution would have to be found if it commences operation.

- All coal-fired power plants may be operated for a maximum of 30 years, calculated from the start of commercial operation.

- From the 21st year of operation onwards, all coal-fired power plants are subject to CO_2 optimized operation, which corresponds in effect to the British *Emission Performance Standard* (EPS), which limits the emissions of a coal-fired power plant to a budget calculated from specific emissions of 450 g CO_2 at a utilization of 85% (DECC 2014, 2015).

- The expansion of the power plant fleet based on renewable energies follows the ambitious scenario described in chapter 5.3.

The way in which CO_2 optimized operation of power plants could be implemented (CO_2 pricing, the auctioning of emission reductions, legal requirements, etc.) is discussed in more detail in chapter 8.2. In the following sections, only the aspects relevant to the development of emissions, production and capacity are analyzed in greater depth.

Figure 7-1: **Net capacity of lignite and hard coal power plants in the Transformation Scenario, 2015–2050**

Source: Calculations by Öko-Institut and Prognos

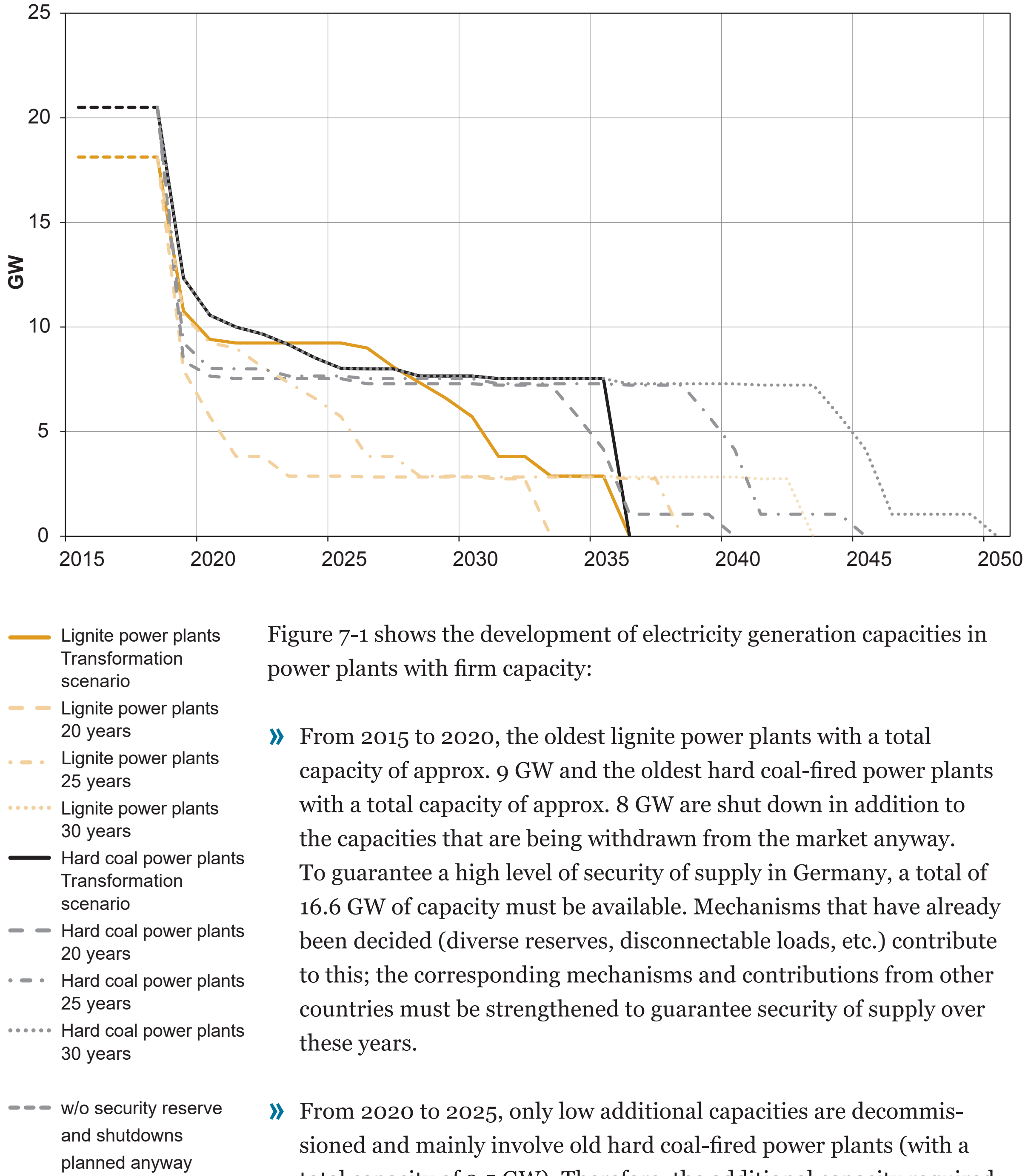


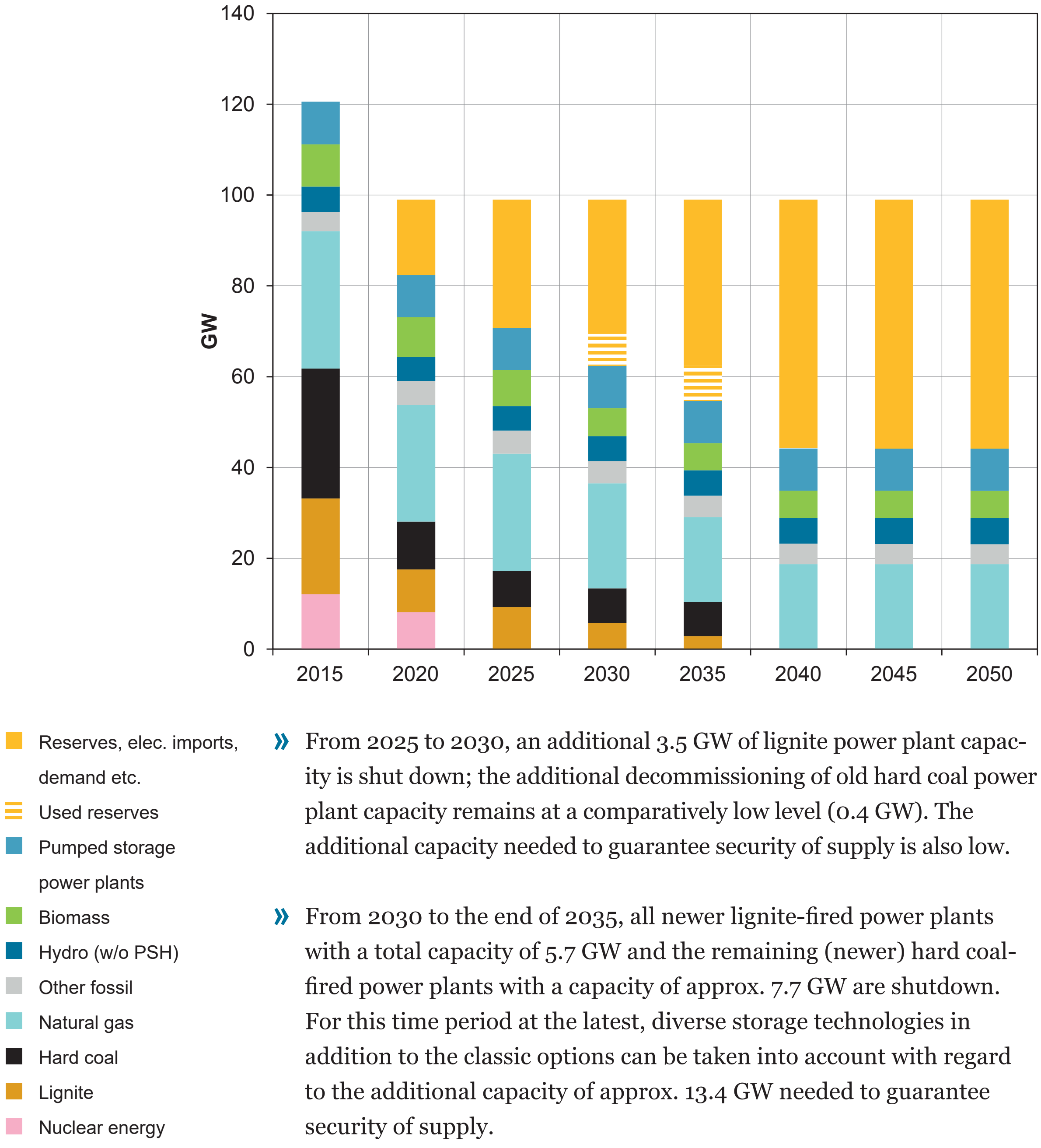
Figure 7-1 shows the development of electricity generation capacities in power plants with firm capacity:

» From 2015 to 2020, the oldest lignite power plants with a total capacity of approx. 9 GW and the oldest hard coal-fired power plants with a total capacity of approx. 8 GW are shut down in addition to the capacities that are being withdrawn from the market anyway. To guarantee a high level of security of supply in Germany, a total of 16.6 GW of capacity must be available. Mechanisms that have already been decided (diverse reserves, disconnectable loads, etc.) contribute to this; the corresponding mechanisms and contributions from other countries must be strengthened to guarantee security of supply over these years.

» From 2020 to 2025, only low additional capacities are decommissioned and mainly involve old hard coal-fired power plants (with a total capacity of 2.5 GW). Therefore, the additional capacity required to guarantee security of supply also remains low.

Figure 7-2: **Firm capacity in the Transformation Scenario, 2015–2050**

Source: Calculations by Öko-Institut and Prognos

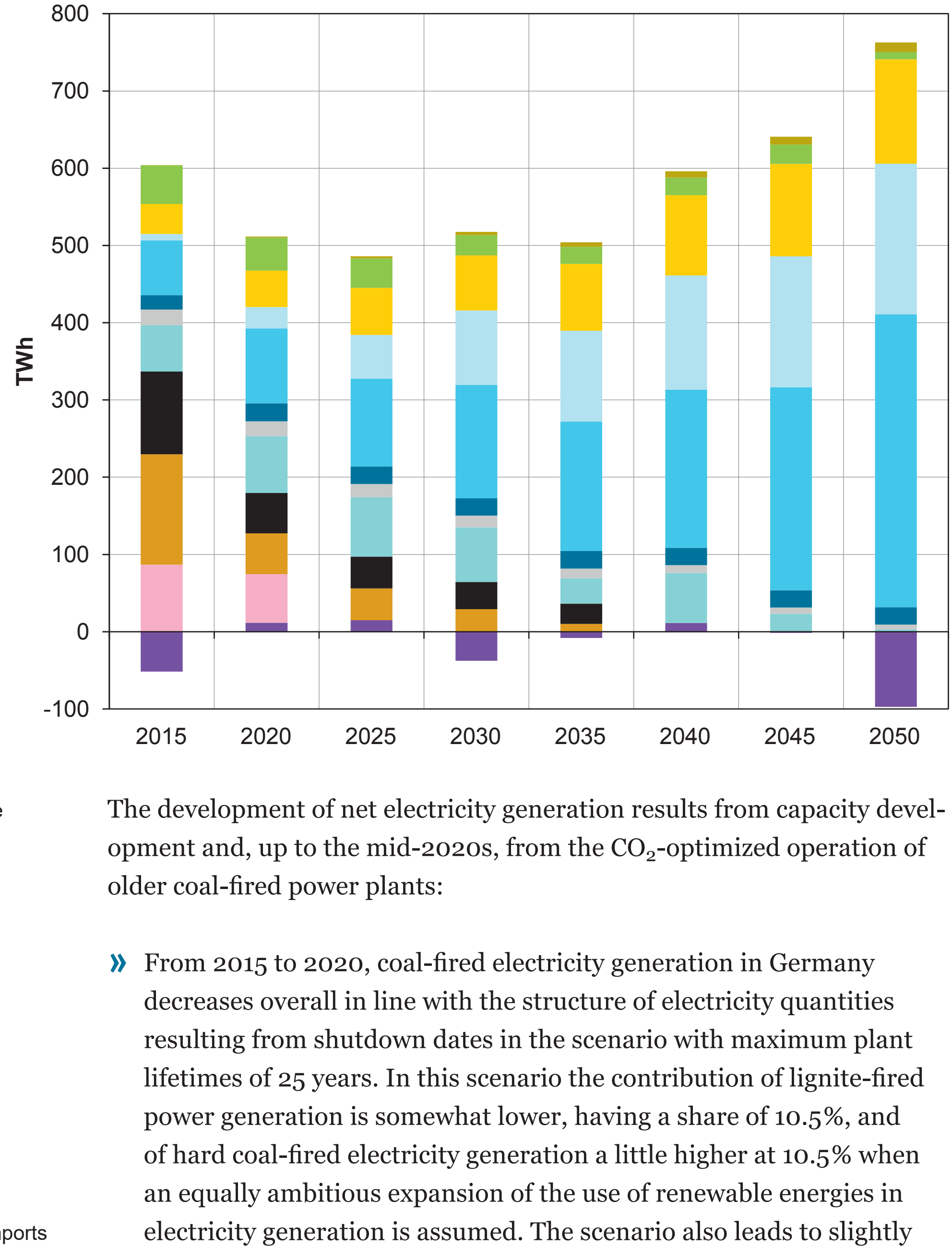


» From 2025 to 2030, an additional 3.5 GW of lignite power plant capacity is shut down; the additional decommissioning of old hard coal power plant capacity remains at a comparatively low level (0.4 GW). The additional capacity needed to guarantee security of supply is also low.

» From 2030 to the end of 2035, all newer lignite-fired power plants with a total capacity of 5.7 GW and the remaining (newer) hard coal-fired power plants with a capacity of approx. 7.7 GW are shutdown. For this time period at the latest, diverse storage technologies in addition to the classic options can be taken into account with regard to the additional capacity of approx. 13.4 GW needed to guarantee security of supply.

In terms of the development of electricity generation capacities, this scenario follows a similar course up to 2030 to the scenario which limits the lifetimes of coal-fired power plants to 30 years; thereafter, it follows the development of the scenario with a 20-year limit on plant lifetime. However, the phases of huge and smaller shutdowns brought about by the concentration of the power plant groupings also indicate that certain flexibilities are possible in the modelling of strictly rule-based decommissioning, without the emission budgets having to be utilized further.

Figure 7-3: **Electricity generation in the Transformation Scenario, 2015–2050** Quelle: Berechnungen von Öko-Institut und Prognos



The development of net electricity generation results from capacity development and, up to the mid-2020s, from the CO_2-optimized operation of older coal-fired power plants:

» From 2015 to 2020, coal-fired electricity generation in Germany decreases overall in line with the structure of electricity quantities resulting from shutdown dates in the scenario with maximum plant lifetimes of 25 years. In this scenario the contribution of lignite-fired power generation is somewhat lower, having a share of 10.5%, and of hard coal-fired electricity generation a little higher at 10.5% when an equally ambitious expansion of the use of renewable energies in electricity generation is assumed. The scenario also leads to slightly higher electricity imports (approx. 10 TWh) and a slightly higher level of domestic electricity generation from natural gas (4 TWh).

» From 2020 to 2025 this trend continues. Power generation based on lignite and hard coal each have shares of approx. 9%; structurally this period is similar to the scenario with plant lifetimes limited to 25 years when an ambitious expansion of the use of renewable energies in electricity generation is assumed. Due to the slightly higher coal-fired power generation compared to the scenario with maximum plant lifetimes of 25 years, natural gas-fired electricity generation is reduced by 6 TWh. There are only slight changes in the balance of electricity imports and exports, with a slight import surplus of about 15 TWh.

- From 2025 to 2030, there is a stronger decrease in the production of lignite power plants due to the larger production share of new hard coal-fired power plants. In 2030 lignite power plants have a share significantly below 6% and hard coal power plants a share slightly below 7% in total power generation. Here, too, the level of natural gas power generation is approx. 15 TWh lower than in the scenario with plant lifetimes limited to 25 years while the surplus electricity exports remain high (approx. 40 TWh).

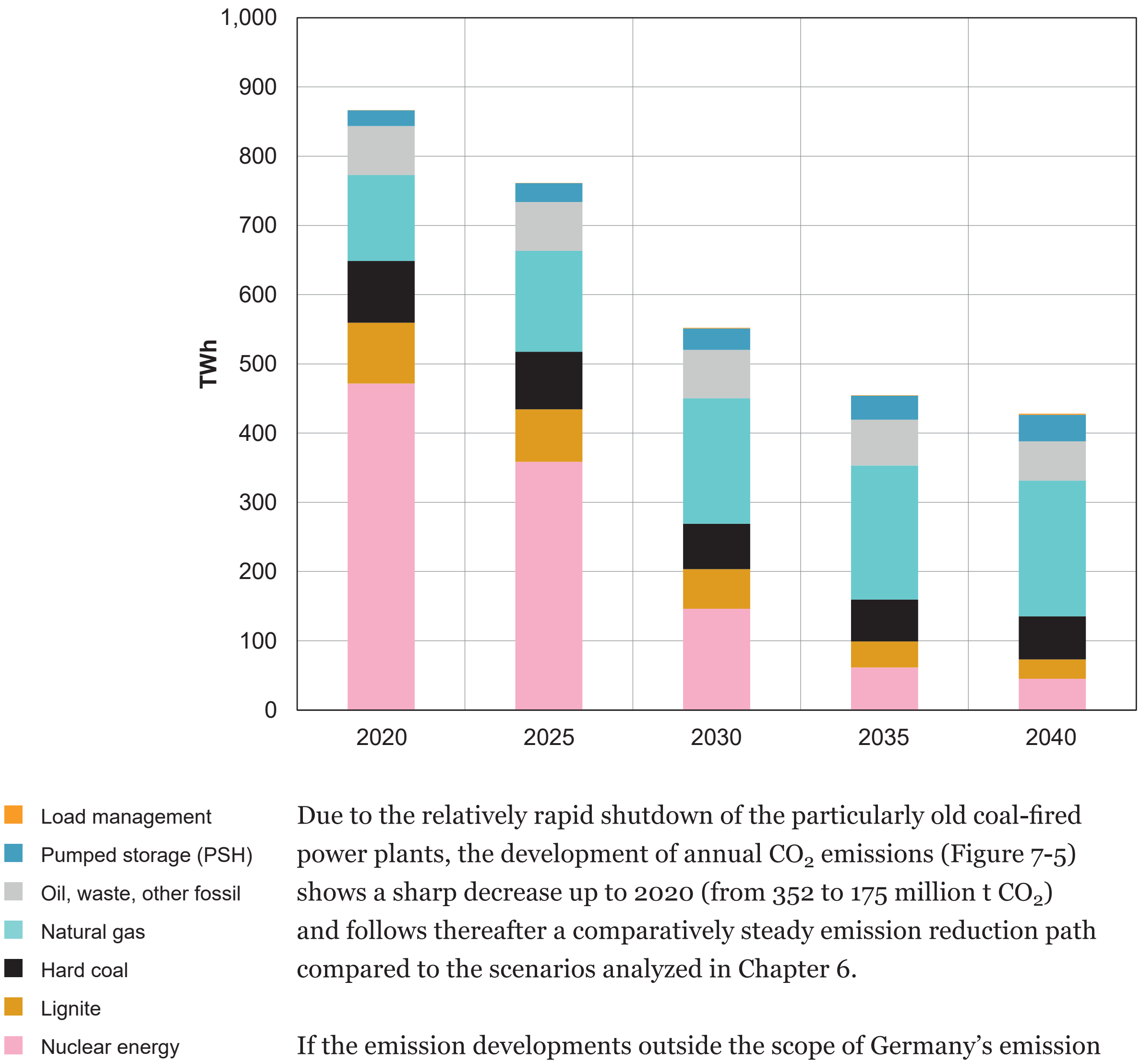
- All coal-fired electricity generation is phased out in Germany by the end of 2035. From 2030 to 2035 the share of hard coal power generation remains larger than that of lignite power plants, due to the comparably younger age of the hard coal power plant fleet. As a result of the decommissioning of younger coal-fired power plants, natural gas-fired power generation increases by approx. 30 TWh. There are significantly smaller changes in the balance of electricity imports and exports (net imports of approx. 10 TWh).

- Under the model assumptions for load profiles as well as the wind and solar power feed-in over the entire scenario period, the reserves needed to guarantee security of supply are utilized on very rare occasions (for a maximum of 10 full load hours with a production contribution of less than 0.1 TWh).

In addition to power generation in Germany, the development of conventional power generation in Germany's electricity neighbours is also relevant in the classification of the transformation scenario. Figure 7-4 presents an overview of these trends; the results for the individual countries are provided in the annex.

Figure 7-4: **Development of conventional electricity generation among Germany's electricity neighbours in the Transformation Scenario**

Source: Calculations by Öko-Institut and Prognos

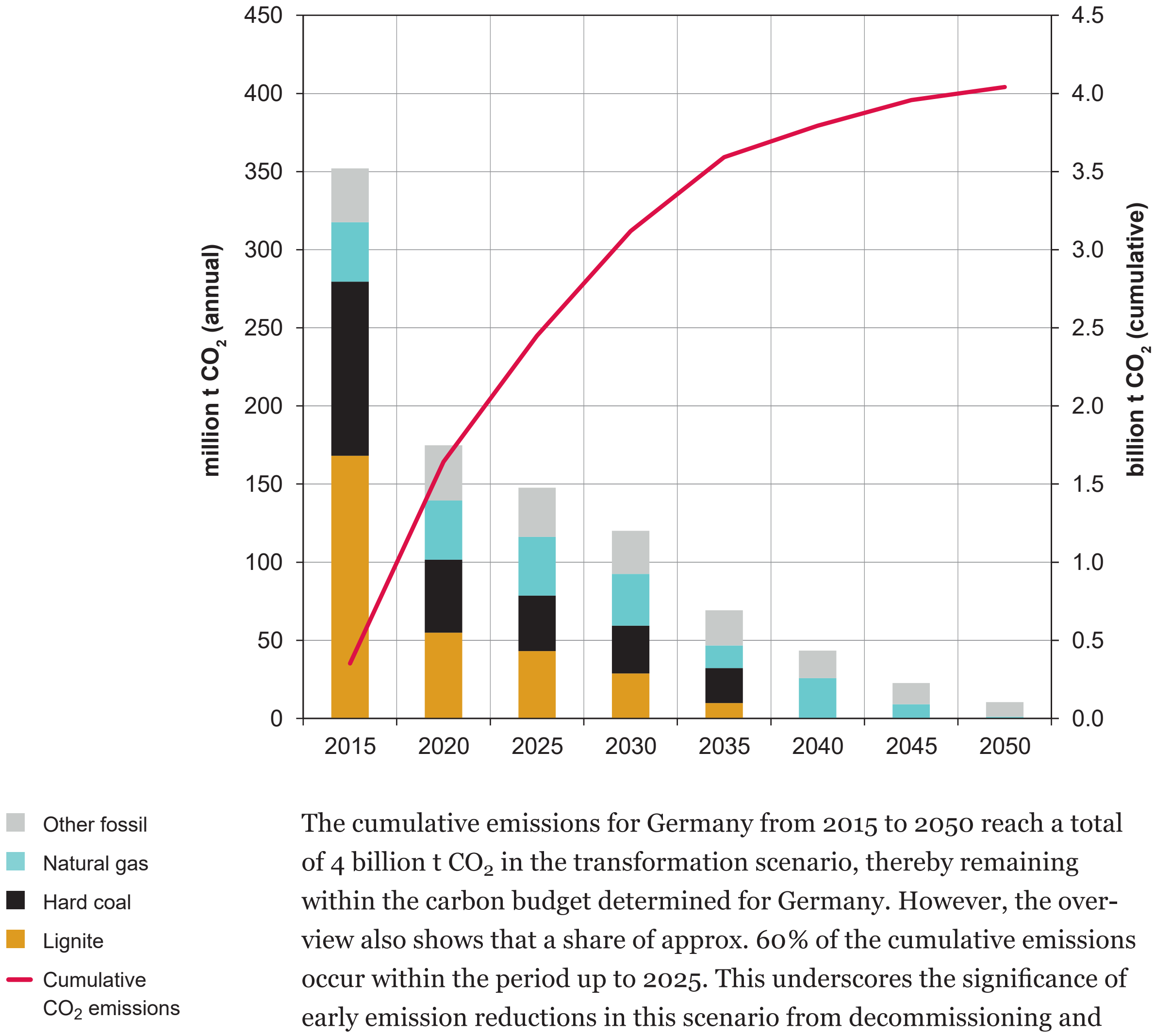


Due to the relatively rapid shutdown of the particularly old coal-fired power plants, the development of annual CO_2 emissions (Figure 7-5) shows a sharp decrease up to 2020 (from 352 to 175 million t CO_2) and follows thereafter a comparatively steady emission reduction path compared to the scenarios analyzed in Chapter 6.

If the emission developments outside the scope of Germany's emission balance are taken into account, additional CO_2 emissions of approx. 2 million t CO_2 arise in other countries as a result of Germany's net electricity imports for 2020. For 2025, this increases to approx. 9 million t CO_2, but remains of minor importance in the overall classification of the emission reductions in the transformation scenario. From 2030 onwards, the emission-increasing effects of Germany's net electricity imports are either no longer generated in other countries or the emission balances of Germany's (electricity) neighbours benefit (slightly) from net exports of electricity from Germany again.

Figure 7-5: **CO_2 emissions in the Transformation Scenario, 2015–2050**

Source: Calculations by Öko-Institut and Prognos

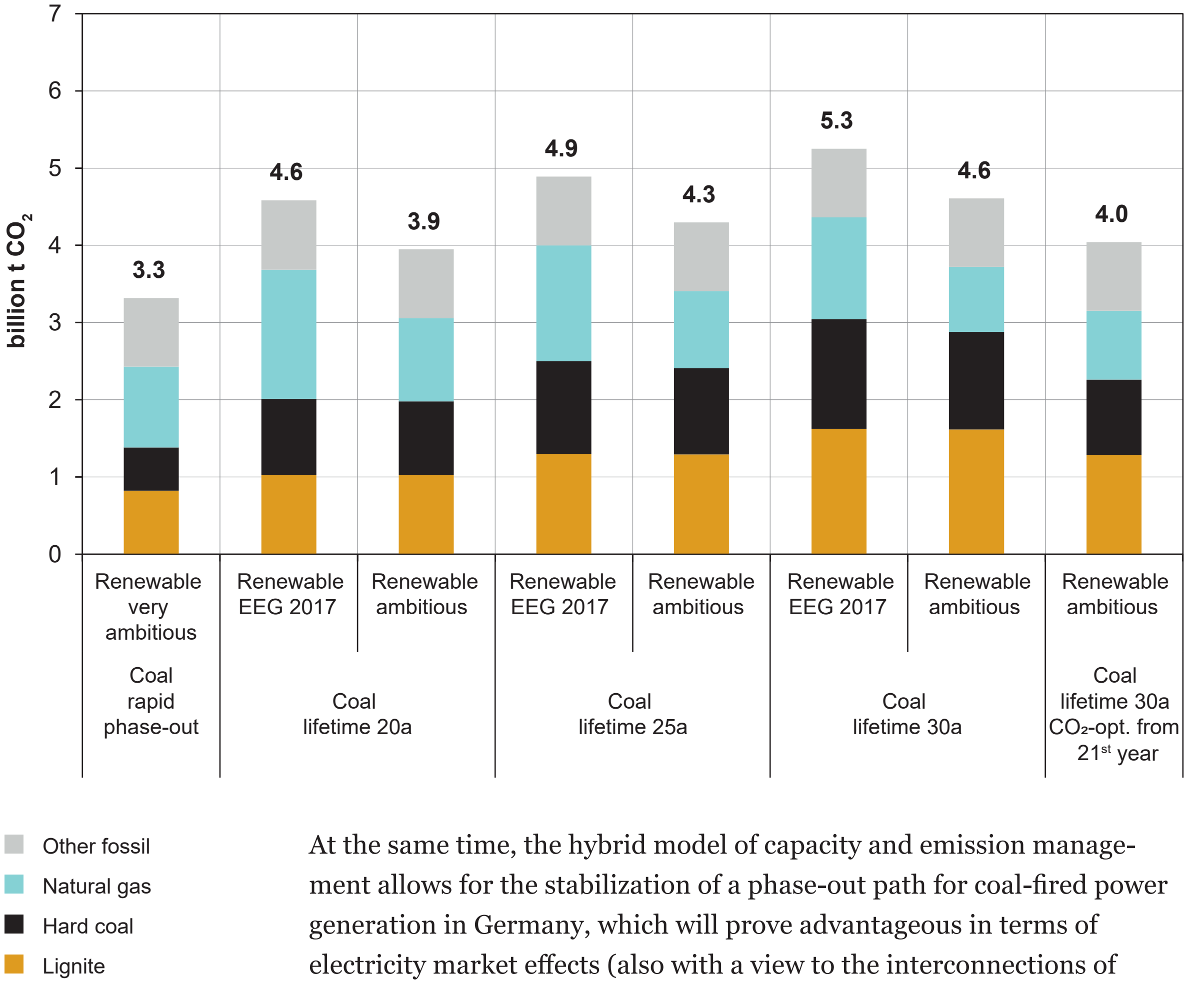


The cumulative emissions for Germany from 2015 to 2050 reach a total of 4 billion t CO_2 in the transformation scenario, thereby remaining within the carbon budget determined for Germany. However, the overview also shows that a share of approx. 60% of the cumulative emissions occur within the period up to 2025. This underscores the significance of early emission reductions in this scenario from decommissioning and CO_2-optimized operation of old power plants, above all in order to limit to a robust level the scope of measures necessary to guarantee security of supply.

The overall classification shows that early emission reductions and the ambitious expansion of renewable energies make crucial contributions to limiting the CO_2 emissions of the electricity system to a budget that is climate-fair in the long term. In the medium and long-term in particular, the increased expansion of electricity generation based on renewable energies plays – in addition to the reduction in coal-fired power generation – a central role in limiting the CO_2 emissions of the remaining power generation from fossil fuels (natural gas etc.).

Figure 7-6: **Cumulative CO_2 emissions in the different scenarios, 2015–2050**

Source: Calculations by Öko-Institut and Prognos



At the same time, the hybrid model of capacity and emission management allows for the stabilization of a phase-out path for coal-fired power generation in Germany, which will prove advantageous in terms of electricity market effects (also with a view to the interconnections of Germany's power system with the systems of neighbouring countries) and the planning and active design of the adaptation processes in the regions concerned. Regarding the latter, it should, however, be noted that similar or substantially more disruptive adaptation needs would arise if the energy market environment develops to the detriment of (lignite) coal-fired electricity generation in both the short and the medium terms and if the adaptation processes have not been initiated at an early stage. In this respect too, the model presented here for the rapid phase-out of coal in Germany constitutes a robust strategy and implementation framework from the perspective of energy and climate policy and a suitable reference framework for regional adaptation strategies.

7.2 Development of wholesale electricity prices

The prices on the wholesale electricity market are based on the short-term marginal costs of the last (marginal) power plant unit used to cover demand. In the short and medium terms, these price levels thus depend predominantly on fuel and CO_2 prices and, especially in the medium and long-term, on the share of power generation options based on renewable energies with short-term marginal costs that are nearly zero, i.e. the share of wind and solar power generation.

In order to be able to distinguish the electricity price effects of different phase-out paths for coal in Germany from the changes brought about by fuel and CO_2 price developments, the prices determined in the model calculations were related to the short-term marginal costs of a modern natural gas combined cycle power plant, which result from the fuel and CO_2 price assumptions for the reference year.[12]

Figure 7-7 shows the results based on the price path "Challenging framework conditions for climate protection" (see chapter 5.1):

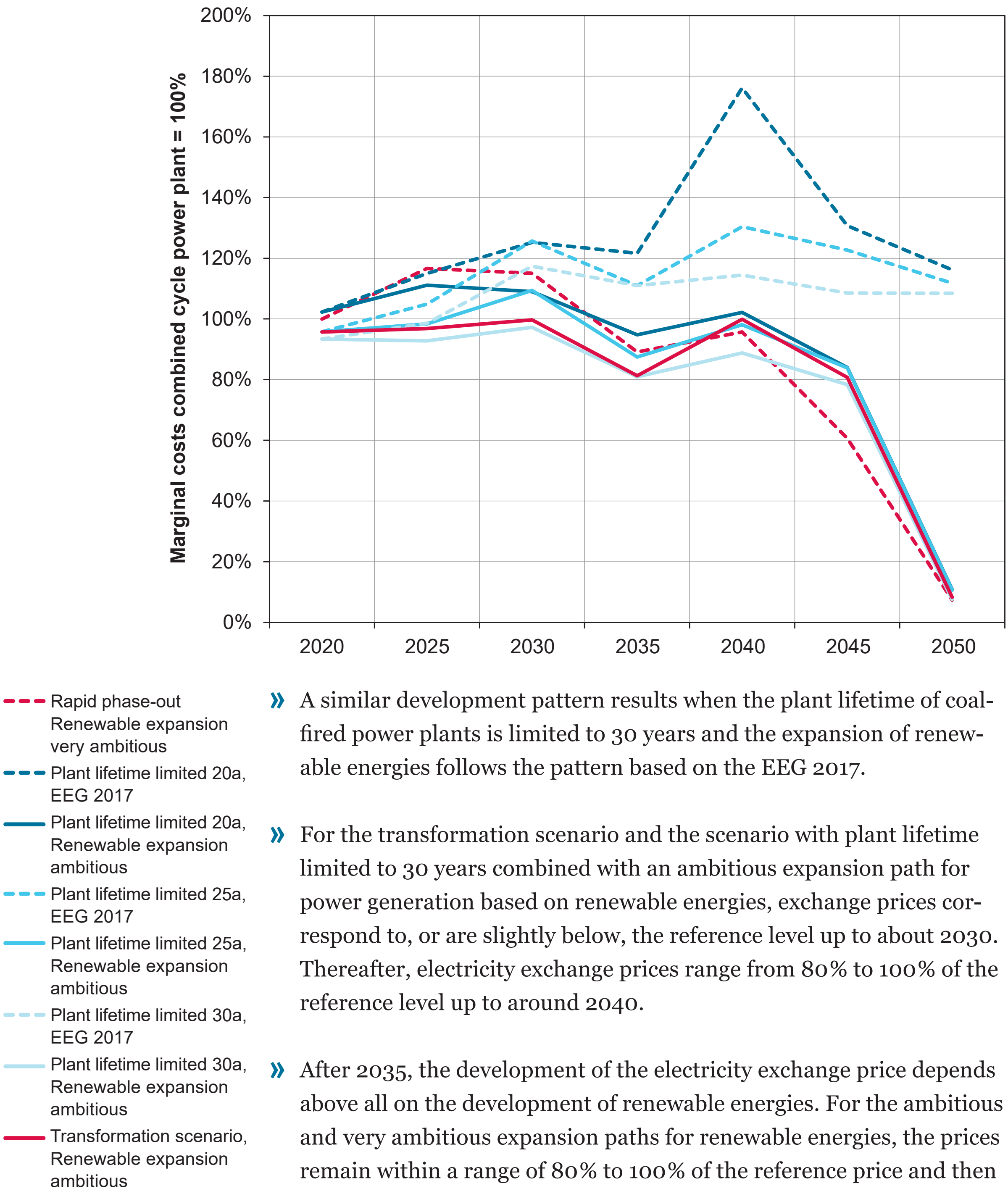
- First of all, the different expansions of renewable energies have very strong effects on the electricity exchange prices. This is particularly the case after 2040 when the exchange prices for the scenarios with the ambitious and very ambitious expansion of power generation based on renewable energies (see chapter 5.3) decrease to very low levels, while in the scenario with the development based on the EEG 2017 fossil-fuelled power plants determine the electricity price in such a high number of hours that the wholesale prices (averaged over the year) remain slightly above the level of short-term marginal costs for a modern natural gas-fired power plant.

- In the scenarios in which very large coal-fired power plant capacities are shut down relatively quickly (i.e. in the rapid phase-out scenario and the scenarios with plant lifetimes limited to 20 and 25 years), the exchange prices for 2025/2030 increase considerably, to approx. 20% above the reference level.

12 For the price scenario "Challenging framework conditions for climate protection" (see chapter 5.1), values of 44 €/MWh are reached for 2020, 61.50 €/MWh for 2030 and 83 €/MWh for 2040. For the complementary price scenario "Beneficial framework conditions for climate protection", the values are 33 €/MWh for 2020, 47 €/MWh for 2030 and 58 €/MWh for 2040.

Figure 7-7: **Effects of different coal phase-out paths on wholesale electricity prices, 2020–2050**

Source: Calculations by Öko-Institut and Prognos



» A similar development pattern results when the plant lifetime of coal-fired power plants is limited to 30 years and the expansion of renewable energies follows the pattern based on the EEG 2017.

» For the transformation scenario and the scenario with plant lifetime limited to 30 years combined with an ambitious expansion path for power generation based on renewable energies, exchange prices correspond to, or are slightly below, the reference level up to about 2030. Thereafter, electricity exchange prices range from 80% to 100% of the reference level up to around 2040.

» After 2035, the development of the electricity exchange price depends above all on the development of renewable energies. For the ambitious and very ambitious expansion paths for renewable energies, the prices remain within a range of 80% to 100% of the reference price and then decrease to very low levels by 2050, as a result of the dominant share of generation options having short-term marginal costs close to zero. In contrast, for the scenario with an expansion of renewable energies based on the EEG 2017 and coal power plant lifetimes limited to 20 and

25 years, there are substantial price increases up to 2040, in an extreme case up to 76% above the reference level. This is because gas-fired power plants with relatively poor efficiencies are price-setting supply options for about a decade.

In the final analysis, the different developments of the price trends show the intensity of system shocks that accompany the accelerated phase-out of coal-fired power generation in Germany based on the various power plant groupings (see chapter 3). These system shocks are of a manageable scale:

- for models based on limiting plant lifetimes that are fully capacity-related and have very long remaining periods (though with emissions that go beyond the emission budget);

- for the hybrid model, which has relatively long remaining periods for capacities but a rapid transition to CO_2-optimized operation of older power plants (which can remain within the emission budget); and

- in all models with an ambitious or very ambitious expansion path for electricity generation based on renewable energies.

Beyond the price-based classification of system shocks, the development of electricity exchange prices naturally shows only a portion of the economic effects resulting from the different designs of coal phase-out paths and the complementary scenarios for the transition to a power system based on renewable energies. It is particularly interesting in this context to note the economic effects of the different scenarios on the expansion of renewable energies.

Based on other analyses on the development of system costs of electricity generation from renewable energies (Öko-Institut 2017), model calculations were carried out for the additional system costs that result for the ambitious and very ambitious expansion paths for renewable energies in electricity generation:

- the additional system costs amount to approx. 77 €/MWh for 2025, approx. 70 €/MWh for 2030, approx. 65 €/MWh for 2035 and approx. 60 €/MWh for 2040, related to the additional power generation based on renewable energies;

» additional costs result for Germany's overall electricity system up to 2025 that amount to approx. 3 €/MWh for the ambitious expansion path and approx. 10 €/MWh for the very ambitious expansion path for renewable energies; the additional costs amount to 9 and 15 €/MWh for 2030 and approx. 11 and 16 €/MWh for 2035 and approx. 13 and 16 €/MWh for 2040.

It should be noted that these costs are not the surcharge laid down in the German EEG but rather the additional system charges. From these additional system charges, the income of the attainable exchange prices (which depend strongly on the fuel and CO_2 prices and the stage reached in the expansion of renewable energies), which decreases substantially over time, is to be deducted.

Alone this approximate calculation shows that the additional costs for the expansion of the power generation based on renewable energies – which become increasingly attractive from a cost perspective – amount to levels below those of the electricity price effects resulting from the ambitious expansion path of renewable energies.

A closer examination of the cost effects of different expansion paths for the use of renewable energies in power generation is not part of the present analysis, but is a key focus of the analysis to be conducted in the second stage of the project.

7.3 Lignite demand and production

Lignite plays a very important role in the development of the German electricity sector in the next few decades for the following reasons:

- Lignite is the most CO_2-intensive fossil fuel used for electricity generation.

- The lignite power plant fleet has a particularly high proportion of old power plants with low conversion efficiency.

- Lignite power plants are predominantly operated by companies that also operate the open-cast mines which provide the lignite. These companies face a very high share of fixed costs, but they can also control the cost allocation and the movement of revenues between the power plants and the open-cast mines.

- Lignite production is concentrated, at least in part, in structurally weak regions, for which more extensive flanking measures are needed in phasing out lignite.

Table 7-1: Lignite reserves and demand in the Transformation Scenario and the related emission potential, 2015–2050

Sources: Calculations by Öko-Institut

	Production 2015	Reserves start of 2015					Transformation Scenario	
		Total	with general operating plan		w/o general operating plan		Total consumption**	Share of reserves***
	mln t	mln t	mln t		mln t		mln t	
Rhineland	95.2	2,574	1,769	69 %	805	31 %	654	37 %
Lusatia	62.5	1,513	999	66 %	514	34 %	457	46 %
Central Germany	18.9	434	326	75 %	108	25 %	185	57 %
Helmstedt	1.5	3	3	100 %	–*	–*	3.0	100 %
Total	**178.1**	**4,524**	**3,098**	**68 %**	**1,427**	**32 %**	**1,299**	**42 %**
	mln t	mln t	mln t		mln t		mln t	
Rhineland	100	2,712	1,864		848		693	
Lusatia	59	1,431	945		486		432	
Central Germany	20	459	345		114		198	
Helmstedt	2	4	4		–*		4	
Total	**181.1**	**4,606**	**3,158**		**1,448**		**1,326**	

Notes: *Lignite production in the Helmstedt district was terminated in 2016 after the reserves of the Schöningen opencast mine were used up. **including the quantities to be used in addition to power generation (for production of lignite products). *** related to the reserves with approved general operating plans

Table 7-1 shows the lignite reserves in Germany's mining districts as well as the current lignite production (2015) and the cumulative lignite demand for the transformation scenario from 2015 to 2050[13]:

- The total reserves in approved lignite plans of the three mining districts.[14] amount to approx. 4.5 billion tonnes of raw lignite. This corresponds to an approx. 25-fold increase in the current lignite production overall, with slight differences between the three districts (Rhineland 27, Lusatia 24, Central Germany 23). About 57% of this portion of the lignite reserves is owned by Rhineland, about 33.5% by Lusatia and about 9% by the Central German district.

- These total lignite reserves represent CO_2 emissions of a total of 4.6 billion tonnes if all these reserves are used and emissions produced. This amount is clearly above the overall emission budget for Germany's electricity sector that is considered reasonable from a climate policy perspective.

- The reserves for which the first (long-term) license has been granted under mining law (general operating plan) amount to a total of 3.1 billion tonnes of raw lignite (corresponding to 3.2 billion t CO_2). Their distribution among the three districts of Rhineland, Lusatia and Central Germany is very similar to the distribution of the overall reserves and correspond to a 19-, 16- and 17-fold increase of the production of 2015. However, it should be pointed out that production can only begin when the main operating plans have been approved (for a 2-year period).

For the Transformation Scenario to remain within the emissions budget determined for the German electricity sector, a maximum of 42% of the lignite reserves (pre)approved in the main operating plans may be mined and produce emissions; in terms of the total reserves this share is only 29%.

13 It should be pointed out that although lignite is predominantly used for electricity generation, the mining quantities shown also include the use of raw lignite for the production of lignite products for use in the heat market, etc. However, for the entire period of 2015 to 2050, the shares for such uses play only a subordinate role (approx. 40 million t raw lignite and 41 million t CO_2).

14 Helmstedt, the fourth mining district, ceased production in 2016 and is not considered in future developments in this analysis. In the Rhineland mining district, the planned down-scaling of the Garzweiler opencast mine has been taken into account.

An analysis of the individual mining districts also shows that the potential tapping of the reserves covered by the operating plans approved to date differs among the individual districts (37% in Rhineland, 46% in Lusatia and 57% in Central Germany). However, it is advisable to curtail rather than expand the mining quantities approved to date.

The structural cost consequences for the various systems from power plants, open-cast mines and the transport infrastructure require a separate analysis, mainly because they are highly dependent on the respective market environment. An analysis of this kind and a closer examination of the regional economic aspects with their (very) different facets were not within the scope of the present study.

It should be noted, however, that a robust solution to the challenges at the core of this analysis is hardly possible without the reliable and transparent definition of a phase-out path for coal-fired electricity generation.

8 Strategies and instruments for implementing the phase-out of coal in Germany

8.1 Strategies for implementing the coal phase-out

From the above analyses and considerations, central elements of the strategy for implementing the phase-out of coal can be derived from the overall objective of limiting the cumulative emissions of the German electricity sector to a total of 4.0 to 4.2 billion tonnes of CO_2 from 2015 to 2050.

These elements can be described, for the time being, independently of the development of concrete instruments for which a number of variations are conceivable and which can certainly change over the course of time (also as a result of changing policy preferences or environmental conditions). However, robust guiding principles for the strategies need to be defined to ensure a certain degree of flexibility in the development of instruments:

» A first key element of such strategies is to accelerate the expansion of electricity generation based on renewable energies. The volumes of electricity generation based on renewable energies have a crucial influence on the CO_2 emission reductions achievable in an accelerated phase-out of coal in electricity generation in Germany, taking into account all feedback effects on the power system. Power generation from renewable energies would have to be approx. 7% higher in 2025, at 295 TWh (instead of 275 TWh as envisaged by EEG 2017) and 25% higher in 2035, at approx. 425 TWh (instead of 340 TWh based on EEG 2017).

» A second key element is the relatively quick shutdown by 2025 of all coal-fired power plants older than 30 years; the reduction of these capacities can and should start in 2019. In designing the merit order and, if necessary, enabling a useful flexibility of this merit order by 2025, it must be taken into account that the power plants concerned are hard coal power plants with relatively low utilization (and correspondingly low emission levels) and lignite power plants with very high utilization (and correspondingly high emission levels).

» The third key element is to have a fixed end date for power generation based on lignite and hard coal in Germany, which should be phased out by the end of 2035. With very few exceptions, it would be possible for newer coal-fired power plants to have a lifetime of at least 20 years after the start of commercial operation. Specific (compensatory) rules would then need to be introduced for the exceptions.

» The fourth key element is to implement a mix of capacity and emissions management, with which a certain consistency in emissions reductions, capacity reductions and electricity market effects can be achieved and adaptation processes for companies and regions can be facilitated from 2025 to 2035. The lifetime of coal-fired power plants is limited to 30 years, calculated from the start of commercial operation. In the last 10 years of this plant lifetime, the power plants are to be operated in a CO_2 optimized way, so that they do not exceed annual emissions of 3.35 tonnes of CO_2 per kilowatt of net capacity on average.

» The fifth key element of the strategies is to reduce Germany's high surplus electricity exports from CO_2-intensive power generation and to strive for balanced electricity exports and imports in the decade average from 2020 onwards, as far as the cross-border exchange of electricity is to be considered not primarily as part of the integration of renewable energies in the European electricity market and thus as emission-neutral in the (national) emission balances.

» In the sixth key element, the instruments for ensuring system stability and security of supply that have already been implemented or are planned should be reviewed in the context of the accelerated phase-out of coal-fired power generation.

» The seventh key element concerns the regulatory framework for opencast lignite mining. If emissions are to remain within the carbon budget for the German electricity sector of between 4.0 and 4.2 billion t CO_2, less than a half of the lignite reserves that have been (pre-) approved in main operations plans in Germany may be used and emissions produced; and with regard to the approved lignite quantities, it is likely that lignite production is terminated in all mining districts earlier than expected.

» In an eighth key element, comprehensive analyses are needed of the regional economic and social effects of an accelerated phase-out of coal-fire power generation and the creation of the necessary range of compensation mechanisms (from expansion of renewable energies, via settlement policy, to the expansion of infrastructure).

These elements of the strategy should be considered largely robust in terms of the overarching objective, the energy market environment and the developments in Germany's neighboring countries and on the European level and serve as the guiding principles for the selection and design of implementation instruments.

8.2 Possible instruments for implementing the coal phase-out

Based on the key elements of strategies for the coal phase-out provided above, implementation instruments can be designed and introduced. Given the diverse guiding principles they contain, it is clear that the implementation instruments cannot be restricted to a single mechanism; instead, a mix of different instruments is necessary. There are a number of further considerations for the design of this mix:

- Both the selection and the design of the policy instruments and their mix depend, in addition to their intended effects, crucially on the premises that underlie their distribution effects. Clear decisions need to be taken on whether the electricity consumers should have the lowest possible burden (assessed on the basis of electricity prices and other refinancing mechanisms of the electricity system such as surcharges or fees) or whether the economic consequences for the utilities should be reduced (assessed on the basis of the electricity market or specific remuneration or compensation mechanisms).

- The political options for action initially depend on the decision of whether to use instruments as purely national mechanisms, within the framework of the several countries (e.g. within the Central-Western European electricity regional market) or as EU-wide instruments. However, the degree to which the fifth element of the strategy is pursued is also relevant here, i.e. the extent to which it is possible for the instruments to avoid negative rebound effects of Germany's power system on the emissions of its electricity neighbours. In any event, the interactions with the EU Emissions Trading System must be taken into account.

With that in mind, three approaches are available for the development of instruments to implement the coal phase-out:

- Legal approaches can directly implement certain requirements; they have a high degree of effectiveness, are comparatively robust in terms of the different conditions of the market environment and predominantly have beneficial effects for electricity consumers from the distribution perspective (to the disadvantage of the plant operators). However, these approaches must meet a number of legal requirements (which cannot be discussed in detail within the scope of the present analysis).

» Pricing approaches aim to change the revenue conditions for particular power plants. With a view to the still very volatile market conditions, pricing approaches must be flexibly or responsively applied if they are to achieve a high degree of effectiveness. On the distribution side, they place a greater burden on the electricity consumers, the more comprehensive they are. For the different companies, the net economic effect depends on the possible loss of contribution margins of the power plants for which decreases in production occur and on the additional revenues from rising wholesale prices.

» Compensation approaches reward the termination or reduction in production with financial compensation determined either administratively or via competition. These approaches are comparatively effective and robust due to the high reliability of the rewards of emission reductions. However, on the distribution side they have a disadvantageous effect on those responsible for making the compensation payments (i.e. the electricity consumers or, where appropriate, the taxpayers) and they reverse, in the final analysis, the polluter pays principle. The affected companies are given additional liquidity; via their feedback effects on the electricity market, such instruments have only a slight positive effect on the revenues of unaffected power generating companies.

Against this background, the following key points result for the development of instruments for the coal phase-out in Germany:

1. The fixed end date for the termination of coal-fired electricity generation in Germany needs to be laid down in a regulation. In terms of the age structures of the power plants concerned, this means a minimum plant lifetime of 20 years, with some exceptions. Given the legal discussions that arose with the phase-out of nuclear power and the differences between the cost structures of coal-fired and nuclear power plants (the latter have higher sunk costs), if legal challenges arise, they are likely to involve young power plants that can only be used commercially for 20 years.

2. The limit on plant lifetimes to a maximum of 30 years can be implemented through regulation or contractual provisions. Both cases can, at least in principle, be combined with compensation payments (as was the case, for example, with Germany's regulation on the lignite security standby, which came into force in 2016). A legal assessment needs to be undertaken of the decision for or against compensation payments; in the final analysis, it is primarily a political decision. There also needs to be an in-depth discussion of whether and to what extent it is possible and useful to calculate compensation payments on a competition basis; this was not included in the scope of the present analysis. It should be noted, however, that this approach reverses the polluter-pays principle and should thus be regarded as less suitable. Finally, in addition to the hardship clauses that are legally required in any case, special regulations are particularly useful and necessary for the decommissioning of coal-fired thermal power plants, which needs to occur relatively quickly.

3. The whole range of instruments can be used to enact CO_2-optimized operation during a specific period of plant lifetime (i.e. from the 21st to the 30th year after the start of commercial operation), which is crucial to keeping within the emission budget[15]:

a) CO_2-optimized plant operation can be implemented on the basis of regulations. The model of the British *Emissions Performance Standard* (EPS), based on which the parameters of the present analyses are also determined (DECC 2014, 2015), is an appropriate point of reference. Such a regulation can undoubtedly be implemented nationally and would have a high degree of integrity in climate policy terms, also with a view to emission developments in neighbouring European countries.

b) It is also possible to bring about CO_2-optimized plant operation on the basis of a minimum price in the EU Emissions Trading System (EU ETS). This minimum price would depend on the energy market environment but would also ensure a high degree of consistency between the strategy for the coal phase-out and the EU ETS. However,

15 The regulatory model of the *Emissions Performance Standard* (EPS) was shown in the numerical electricity market analyses. The reason for this was that by showing CO_2-optimized operation in this way, the purely instrument-related distribution effects of the different implementation options can be largely blended out. However, with a view to the hybrid approach in this analysis, this does not mean that an EPS is the only option for CO_2 optimization from the 21st year of operation onwards. The (distribution) effects that result solely from the alternative instruments should be analyzed separately.

national implementation of a uniform minimum CO_2 price is problematic in terms of the cross-border integrity of this instrument since the economic situation of all kinds of production in other countries would be improved compared to the corresponding German power generation plants and would result in high emission shifts that do not change the total emission levels. A different situation arises if the minimum CO_2 price is introduced in a framework that integrates different countries – ideally but not necessarily within the framework of the EU as a whole, and usefully within the framework of the countries of the Central-Western European electricity regional market.

c) In contrast, selective CO_2 pricing – e.g. of old coal-fired power plants based on the special levy on coal that was much discussed in Germany in 2015 (BMWi 2015a, Öko-Institut and Prognos 2015) – would be effective as a purely national measure and have a high degree of integrity in climate policy terms from the cross-border perspective. With regard to pricing options, the preferences of instrument and distribution policy as well as opportunities for action on cross-border activities are decisive.

d) Finally, CO_2-optimized plant operation – especially in the case of emission-intensive and old electricity generation plants – can also be achieved by means of (limited) compensation payments. This approach can be implemented on a national level in principle and would also be sound from a climate policy perspective in terms of the cross-border emission effects. Whether and to what extent competitive procedures are possible and can be helpful in determining compensation payments or whether challenges relating to state aid law arise requires an in-depth discussion that was not possible within the scope of this study. Here, too, it should be noted that these compensation approaches reverse the polluter-pays principle, as a result of which this option should be viewed as less suitable.

4. Finally, the dismantling and renaturation of opencast mining areas should be financially secured with the strict participation of the polluters. Expansions of existing opencast mines should not be pursued further; legally secure approaches to reasonable and necessary reductions of existing opencast mining must be developed relatively quickly.

From an overall perspective, therefore, a broad range of options is available for developing instruments to phase out the use of coal in electricity generation in Germany by 2035. These options can be implemented in the context of very different policy preferences and (European) policy framework conditions.

In addition to the implementation of an accelerated phase-out of coal-fired electricity generation in Germany in narrow climate and energy policy terms, further measures have to be taken to embed the coal phase-out more broadly (social and regional economic adaptation strategies for lignite mining areas, incorporation in future power market design, infrastructural aspects). These measures were not included in the present study; they cannot, however, be meaningfully conceived and implemented without determination of the phase-out path for coal-fired electricity generation.

8.3 Excursus: Interactions with the EU Emissions Trading System

The Emissions Trading System of the European Union constitutes an important framework for European climate policy, as do complementary national or regional strategies that strive for a higher level of climate policy integrity in the development of Germany's electricity sector.
It should be noted that the framework of the EU ETS is not consistent with a fair share of efforts to keep within the 2°C limit on the increase in global average temperature, as derived and substantiated in Chapter 4:

- By applying linear reduction factors of 1.74% (up to 2020) and 2.2% (from 2021) to an annually defined quantity of emission allowances, cumulative emissions that total 43.47 billion t CO_2 are calculated for the period from the beginning of 2015 to the end of 2050.

- In addition, surplus carbon credits amounting to 2,127 billion had been generated by the beginning of 2015 from unused emissions allowances and international carbon credits (which predominantly have a questionable environmental integrity), with the result that an overall budget of approx. 45.6 billion t CO_2 is available up to 2050.

- If an example division of this budget is carried out based on the emission levels of 2015, German electricity generation would have a share of approx. 20% or 8.9 billion t CO_2 from 2015 to 2050. Even if the share of emission allowances available to the German power system (in competition) was smaller, it is clear that the current design of the EU ETS is not consistent with the 2°C limit on the increase in global temperature and that the EU ETS needs to be adapted further on this basis.

However, with regard to this need to reform the EU ETS, the question arises as to whether national, regional or European measures to accelerate emission reductions are ineffective from a climate policy perspective if the number of emission allowances available in the long term via the EU ETS does not change. With additional mitigation measures in the European emission balance area, the demand for emission allowances for compliance purposes decreases; in principle, these allowances remain available to other electricity generation plants and/or other industry sectors in and outside of Germany.

Beyond this very abstract finding, however, it should be borne in mind that the EU ETS, which has been purely a quantity control system up to now, is converted into a hybrid system (MSR-RL) based on the rules planned for the fourth trading period (2021-2030). It has been agreed that a Market Stability Reserve (MSR) is to be introduced, based on which the number of emission allowances in circulation and thus usable for compliance is adjusted depending on the respective emission levels, by transferring allowances into the reserve (loading mechanism) or releasing them on to the market (release mechanism). This plan to change the structure of the EU ETS must be considered in the assessment of the effective emission reduction impacts of complementary measures to the EU ETS.

To appreciate the effects of the EU ETS that arise with the introduction of the market stability reserve (MSR), it is helpful to examine the effects for the short, medium and long-terms:

1. In the short term, i.e. up to and including 2020, there are emission reductions in the context of an EU ETS with huge surpluses (more than 2 billion emission allowances). If there is no scarcity of emission allowances (at a specific point in time), an emission reduction in one sector or country does not mean that there is an increase in emissions in another sector or country. For 2020, additional emission reduction measures also lead to additional emission reductions within the current regulatory environment of the EU ETS and thus also to effective contributions to achieving reduction targets both on the German and the European levels.

2. In the medium term, i.e. from 2020 to at least 2030, the additional emission allowances made available by emission reduction measures introduced to complement the EU ETS are fully absorbed by the loading mechanism of the MSR, which limits the surplus to below 833 million emission allowances. The system therefore does not make available more emission allowances than those available in the counterfactual development in the medium term; their use for compliance purposes could compensate the above-mentioned emission reductions. This also means that the additional measures – with the discounting factors assumed in this analysis – do not have an effect on the prices of emission allowances in the future. Consequently, the emission levels in the surplus phase of the system are not higher in the short and medium term. In the medium term, too, real emission reductions and contributions to target achievement are generated, even when the feedback effects of the EU ETS are considered.

3. In the long term, such feedback effects could arise if the emission allowances absorbed in the loading phase of the MSR (see above) are made available again for compliance purposes. According to many current estimates, however, these effects only arise well after 2030; they also assume that the emission allowances in the MSR are not permanently removed from the EU ETS in the next two decades. There are currently no statutory provisions which plan to do this, but it remains a conceivable option – and is being discussed – with a view to stabilizing the carbon market in the long term. The short- and medium-term effects on the current emission allowance prices that may be returned to the market in the distant future is nevertheless negligible because of the very long discounting periods.

As national, regional or EU-wide complementary measures and effect-stabilizing complementary mechanisms, additional emission reduction measures thus definitely result in additional contributions to the achievement of climate targets in the short and medium terms, also when the EU ETS is considered. These measures stabilize the emission reduction path and thereby contribute to avoiding disruptive price developments in the EU ETS and also to the stabilization of the EU ETS.

Nevertheless, the number of emission allowances available via the EU ETS overall must be reduced in the long term, particularly with a view to the concept of emission budgets. The cancellation of emission allowances therefore remains an important task; even if the measures needed for this are useful and desirable in the short term, in terms of reliable framework conditions, they do not necessarily have to be implemented quickly in the final analysis. The following measures are (where appropriate, in combination) useful and target-orientated:

» Emission allowances in the MSR are cancelled, either after a specific period of time (as a comparatively easy-to-implement option) or based on an emission-related assessment of possible policy measures beyond the EU ETS.

» The emission allowances made additionally available each year are reduced by retaining and cancelling a portion of the emission allowances available to the respective EU Member States for auctioning.

» The linear reduction factor is tightened again (substantially), which will considerably reduce the number of emission allowances introduced to the EU ETS each year.

The implementation of a phase-out path for the use of coal in electricity generation in Germany is thus – also with a view to the effects of the EU ETS – sound from a climate policy perspective, if the EU ETS can be correspondingly reformed in the next one to two decades. The regular review mechanisms of the Paris Agreement with its clear reference to the 2°C limit on the rise in global temperature will, over time, increase the pressure to act, foreseeably to a substantial degree. In the short to medium term, until the regulations on the cancellation of emission allowances are introduced, no counterproductive effects are expected for climate policy through the adaptation of the EU ETS that is currently being discussed. Nevertheless, it would be beneficial, and in the interests of a transparent and robust framework, to take the first steps, in the current processes on the structural reform of the EU ETS, towards introducing the possibility of cancelling emission allowances.

9 Conclusions and Outlook

Since the Paris Agreement was adopted in 2015 and came into force in 2016, the 2°C limit on global warming has moved towards the fore of climate policy analyses and strategies. It also necessitates a change of perspective, with a less rigid focus on emission reduction targets for specific time horizons and a stronger consideration of the concept of emission budgets, which is more useful with a view to the targeted effects of the measures. Correspondingly, the quantities of greenhouse gases released into the atmosphere at a given time are less crucial to the achievement of climate targets; it is much more important to consider the total emissions over the entire time frame.

The analyses show, first of all, that an operationalization of the emission budget concept, based on global climate modelling and transparent distribution criteria, is possible for individual countries. The concept of emission budgets geared to specific countries (derived using a global per capita approach and without taking into account historical emissions) and sectors (derived using approximately proportional emission reductions in the different sectors) is a productive approach to identifying "fair share" contributions to the achievement of global climate targets.

With regard to greenhouse gas emissions, it is possible pragmatically to convert national emission budgets for large or dominant polluters into robust sectoral budgets. Based on an emissions budget for Germany of approx. 10 billion t CO_2 from 2015 to 2050, a corresponding emissions budget of 4.0 to 4.2 billion t CO_2 results for the German electricity sector. The large role played by coal-fired electricity generation in Germany's CO_2 emissions overall and in Germany's power sector in particular makes a rigorous phase-out of hard coal and lignite electricity generation essential, if short, medium and long-term climate targets are to be achieved.

The modelling of very different approaches for such a coal phase-out shows that there is a considerable scope for measures on the termination of coal-fired electricity generation, which utilize the carbon budget to different extents. However, the modelling also shows very different implications for the continuity of the transformation process, the implications and need for action regarding security of supply, the cross-border effects in the Continental European electricity market and the cost development.

The resulting model for a robust phase-out path for coal in Germany's power generation consists of a mix of:

- the quick decommissioning of particularly old lignite- and hard coal-fired power plants;
- a combination (that takes effect in the medium term) of the stepwise shutdown of plants, based on a maximum plant lifetime of 30 years;
- CO_2-optimized plant operation after the 20th year of operation (from the perspective of the polluter pays principle, either through regulatory instruments like the Emissions Performance Standards or via the broad range of pricing models and, less suitably, via buy-out (compensation) approaches); and
- a fixed end date for coal-fired electricity generation in 2035.

Long-term robust elements were drawn from these model considerations for coal phase-out strategies, on the basis of which different concrete instruments and variants of these can be derived. A large number of variations of instruments for these elements is possible and allows considerable flexibility, also over time. The same applies to possible opportunities for concerted policy activities in the European Union or with Germany's neighbouring countries.

In light of this, further research needs to be conducted on the implementation of the phase-out path for coal use in electricity generation. This should consider the following:

1. What packages of measures can be considered advantageous or particularly promising in terms of a purely national approach or concerted action with Germany's neighbouring countries?
2. What are the legal framework conditions for the individual elements of the instruments and for the proposed mix of approaches?
3. What distribution effects are acceptable in certain policy contexts, what preferences or combinations of preferences can promote concrete political implementation measures in this respect?

4. What special rules can be introduced, especially in the short term, for the decommissioning of lignite and hard coal-fired combined heat and power plants to ease tensions between guaranteeing security of supply and the achievement of necessary emission reductions?

5. Since any strategy to accelerate emission reductions in the electricity sector must have particularly strong effects on lignite-fired electricity generation and since very specific regional economic challenges with long-term adaptation processes arise, it is essential for an in-depth analysis to be conducted of the different options available for necessary flanking policies in the design of a reliable phase-out path.

However, the design of an electricity sector that keeps within its emissions budget is not just a question of a consistent coal phase-out. The model analyses have clearly shown that an ambitious (and accelerated) expansion of the use of renewable energies in electricity generation is a crucial success factor. Corresponding expansion paths were provided in the analyses of this study. There is also a need for further research in this respect:

6. What aspects of the expansion of electricity generation based on renewable energies are conceivable under what premises and framework conditions with regard to decentralization, proximity to point of consumption, need for electricity storage, scope for optimization etc., and how can these be assessed?

7. What contributions can these different designs of development paths on the issues identified in the present study (e.g. relating to security of supply) make to firm capacity (e.g. with a view to contributions of electricity storage) in the context of a phase-out of coal-fired power generation?

The second phase of the project in which this study was conducted will provide an in-depth analysis of the latter two questions in particular.

10 References

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Annex 1: Detailed tables of results

Table A-1
Results of the rapid phase-out scenario with a very ambitious expansion of renewable energies, 2015–2050
Source: Calculations by Öko-Institut and Prognos

	2015	2020	2025	2030	2035	2040	2045	2050
Production capacity	GW (net)							
Nuclear energy	12	8	-	-	-	-	-	-
Lignite	21	7	-	-	-	-	-	-
Hard coal	29	7	-	-	-	-	-	-
Natural gas	30	26	26	23	19	19	19	19
Other fossil	4	5	5	5	5	5	4	4
Hydro (w/o PSH)	6	5	5	5	6	6	6	6
Wind onshore	41	55	65	78	84	97	122	173
Wind offshore	3	6	18	27	33	39	45	51
PV	39	54	73	84	101	117	134	150
Biomass	9	9	8	6	6	6	6	6
Other renewable	-	0	0	1	1	1	2	2
Short-term storage (incl. PSH)	9	9	9	9	9	9	9	9
Reserves, DSM, Imports	-	23	46	50	55	55	55	55
Total	**204**	**215**	**255**	**289**	**318**	**353**	**402**	**475**
Total firm capacity	*121*	*99*	*99*	*99*	*99*	*99*	*99*	*99*
Electricity generation	TWh (net)							
Nuclear energy	87	63	-	-	-	-	-	-
Lignite	143	47	-	-	-	-	-	-
Hard coal	107	40	-	-	-	-	-	-
Natural gas	59	80	110	98	51	56	15	2
Other fossil	21	19	18	15	13	10	8	6
Hydro	19	23	23	22	22	22	22	22
Wind onshore	71	103	130	164	185	223	281	397
Wind offshore	8	28	75	115	131	167	187	197
PV	39	50	68	79	94	111	127	143
Biomass	50	42	38	26	22	23	25	6
Other renewable	0	1	3	4	6	8	10	12
Total generation	**604**	**496**	**465**	**524**	**524**	**621**	**675**	**786**
renewable share	*187*	*247*	*336*	*410*	*461*	*555*	*652*	*778*
Net electricity imports	-52	6	24	-34	-22	-14	-8	-79
CO_2 emissions	million t CO_2							
Lignite	168	47	-	-	-	-	-	-
Hard coal	111	34	-	-	-	-	-	-
Natural gas	38	37	51	44	21	22	6	1
Other fossil	34	36	32	28	23	18	14	9
Total	**352**	**153**	**83**	**72**	**44**	**40**	**20**	**10**
Cum. CO_2 emissions	million t CO_2							
Lignite	168	705	821	821	821	821	821	821
Hard coal	111	475	560	560	560	560	560	560
Natural gas	38	226	447	685	849	958	1,029	1,047
Other fossil	34	209	378	528	654	754	833	890
Total	**352**	**1,615**	**2,206**	**2,594**	**2,884**	**3,094**	**3,243**	**3,318**

Table A-2
Results for scenario with plant lifetime limit of 20 years and an expansion of renewable energies based on EEG 2017, 2015–2050

Source: Calculations by Öko-Institut and Prognos

	2015	2020	2025	2030	2035	2040	2045	2050
Production capacity	GW (net)							
Nuclear energy	12	8	-	-	-	-	-	-
Lignite	21	6	3	3	-	-	-	-
Hard coal	29	8	8	7	4	-	-	-
Natural gas	30	26	26	23	19	19	19	19
Other fossil	4	5	5	5	5	5	4	4
Hydro (w/o PSH)	6	5	5	5	6	6	6	6
Wind onshore	41	52	54	59	62	68	80	105
Wind offshore	3	7	11	15	19	23	27	31
PV	39	51	62	66	75	84	93	102
Biomass	9	9	8	6	6	6	6	6
Other renewable	-	0	0	1	1	1	2	2
Short-term storage (incl. PSH)	9	9	9	9	9	9	9	9
Reserves, DSM, Imports	-	23	35	40	51	55	55	55
Total	**204**	**209**	**227**	**239**	**256**	**275**	**301**	**339**
Total firm capacity	*121*	*99*	*99*	*99*	*99*	*99*	*99*	*99*
Electricity generation	TWh (net)							
Nuclear energy	87	63	-	-	-	-	-	-
Lignite	143	41	19	20	-	-	-	-
Hard coal	107	42	39	43	25	-	-	-
Natural gas	59	88	116	114	93	146	115	100
Other fossil	21	19	18	16	13	11	8	6
Hydro	19	23	23	22	22	22	22	22
Wind onshore	71	97	108	123	136	156	184	241
Wind offshore	8	28	45	65	81	99	116	133
PV	39	47	58	62	70	80	89	97
Biomass	50	43	38	27	23	25	28	31
Other renewable	0	1	3	4	6	8	10	12
Total generation	**604**	**492**	**468**	**497**	**469**	**547**	**572**	**645**
renewable share	*187*	*239*	*275*	*303*	*338*	*390*	*449*	*538*
Net electricity imports	-52	11	22	-10	33	57	73	24
CO_2 emissions	million t CO_2							
Lignite	168	40	18	20	-	-	-	-
Hard coal	111	36	33	36	21	-	-	-
Natural gas	38	45	55	52	39	62	44	37
Other fossil	34	36	32	28	23	18	14	9
Total	**352**	**156**	**139**	**135**	**82**	**80**	**58**	**47**
Cum. CO_2 emissions	million t CO_2							
Lignite	168	736	882	978	1,026	1,026	1,026	1,026
Hard coal	111	445	617	791	933	985	985	985
Natural gas	38	212	462	730	955	1,207	1,472	1,675
Other fossil	34	211	381	532	659	760	839	897
Total	**352**	**1,603**	**2,343**	**3,030**	**3,573**	**3,978**	**4,322**	**4,582**

Table A-3
Results for scenario with plant lifetime limit of 25 years and an expansion of renewable energies based on EEG 2017, 2015–2050

Source: Calculations by Öko-Institut and Prognos

	2015	2020	2025	2030	2035	2040	2045	2050
Production capacity				GW (net)				
Nuclear energy	12	8	-	-	-	-	-	-
Lignite	21	9	6	3	3	-	-	-
Hard coal	29	8	8	8	7	5	-	-
Natural gas	30	26	26	23	19	19	19	19
Other fossil	4	5	5	5	5	5	4	4
Hydro (w/o PSH)	6	5	5	5	6	6	6	6
Wind onshore	41	52	54	59	62	68	80	105
Wind offshore	3	7	11	15	19	23	27	31
PV	39	51	62	66	75	84	93	102
Biomass	9	9	8	6	6	6	6	6
Other renewable	-	0	0	1	1	1	2	2
Short-term storage (incl. PSH)	9	9	9	9	9	9	9	9
Reserves, DSM, Imports	-	19	32	40	45	50	55	55
Total	**204**	**209**	**227**	**239**	**256**	**275**	**301**	**339**
Total firm capacity	*121*	*99*	*99*	*99*	*99*	*99*	*99*	*99*
Electricity generation				TWh (net)				
Nuclear energy	87	63	-	-	-	-	-	-
Lignite	143	63	38	21	19	-	-	-
Hard coal	107	42	36	45	40	32	-	-
Natural gas	59	78	99	114	71	116	109	94
Other fossil	21	19	18	16	13	10	8	6
Hydro	19	23	23	22	22	22	22	22
Wind onshore	71	97	108	123	136	156	184	241
Wind offshore	8	28	45	65	81	99	116	133
PV	39	47	58	62	70	80	89	97
Biomass	50	43	38	27	22	24	27	31
Other renewable	0	1	3	4	6	8	10	12
Total generation	**604**	**504**	**466**	**498**	**481**	**547**	**565**	**638**
renewable share	*187*	*239*	*275*	*303*	*338*	*389*	*448*	*538*
Net electricity imports	-52	-0	24	-12	20	57	80	30
CO_2 emissions				million t CO_2				
Lignite	168	66	37	20	19	-	-	-
Hard coal	111	36	31	38	33	26	-	-
Natural gas	38	40	48	52	30	45	41	35
Other fossil	34	36	32	28	23	18	14	9
Total	**352**	**177**	**148**	**137**	**104**	**89**	**55**	**44**
Cum. CO_2 emissions				million t CO_2				
Lignite	168	753	1,011	1,153	1,250	1,297	1,297	1,297
Hard coal	111	480	648	820	995	1,141	1,205	1,205
Natural gas	38	232	451	699	903	1,091	1,307	1,496
Other fossil	34	210	379	529	655	756	835	892
Total	**352**	**1,676**	**2,489**	**3,201**	**3,803**	**4,284**	**4,643**	**4,890**

Table A-4
Results for scenario with plant lifetime limit of 30 years and an expansion of renewable energies based on EEG 2017, 2015–2050

Source: Calculations by Öko-Institut and Prognos

	2015	2020	2025	2030	2035	2040	2045	2050
Production capacity	GW (net)							
Nuclear energy	12	8	-	-	-	-	-	-
Lignite	21	9	9	6	3	3	-	-
Hard coal	29	11	8	8	8	7	4	-
Natural gas	30	26	26	23	19	19	19	19
Other fossil	4	5	5	5	5	5	4	4
Hydro (w/o PSH)	6	5	5	5	6	6	6	6
Wind onshore	41	52	54	59	62	68	80	105
Wind offshore	3	7	11	15	19	23	27	31
PV	39	51	62	66	75	84	93	102
Biomass	9	9	8	6	6	6	6	6
Other renewable	-	0	0	1	1	1	2	2
Short-term storage (incl. PSH)	9	9	9	9	9	9	9	9
Reserves, DSM, Imports	-	17	28	37	44	45	51	55
Total	**204**	**209**	**227**	**239**	**256**	**275**	**301**	**339**
Total firm capacity	*121*	*99*	*99*	*99*	*99*	*99*	*99*	*99*
Electricity generation	TWh (net)							
Nuclear energy	87	63	-	-	-	-	-	-
Lignite	143	64	59	40	20	20	-	-
Hard coal	107	52	36	43	41	46	27	-
Natural gas	59	72	88	99	71	92	84	86
Other fossil	21	19	18	16	13	10	8	6
Hydro	19	23	23	22	22	22	22	22
Wind onshore	71	97	108	123	136	156	184	241
Wind offshore	8	28	45	65	81	99	116	133
PV	39	47	58	62	70	80	89	97
Biomass	50	43	38	27	22	24	26	31
Other renewable	0	1	3	4	6	8	10	12
Total generation	**604**	**511**	**475**	**500**	**483**	**558**	**567**	**630**
renewable share	*187*	*239*	*276*	*302*	*338*	*389*	*448*	*537*
Net electricity imports	-52	-7	15	-14	19	45	78	39
CO_2 emissions	million t CO_2							
Lignite	168	67	61	40	19	20	-	-
Hard coal	111	47	31	36	34	38	22	-
Natural gas	38	37	42	45	30	36	31	31
Other fossil	34	35	32	28	23	18	14	9
Total	**352**	**187**	**166**	**148**	**105**	**111**	**66**	**41**
Cum. CO_2 emissions	million t CO_2							
Lignite	168	757	1,078	1,330	1,477	1,574	1,623	1,623
Hard coal	111	507	700	868	1,042	1,219	1,367	1,421
Natural gas	38	226	424	642	828	993	1,161	1,317
Other fossil	34	209	378	527	653	754	832	890
Total	**352**	**1,699**	**2,580**	**3,366**	**4,000**	**4,540**	**4,983**	**5,251**

Table A-5
Results for scenario with plant lifetime limit of 20 years and an ambitious expansion of renewable energies, 2015–2050

Source: Calculations by Öko-Institut and Prognos

	2015	2020	2025	2030	2035	2040	2045	2050
Production capacity	**GW (net)**							
Nuclear energy	12	8	-	-	-	-	-	-
Lignite	21	6	3	3	-	-	-	-
Hard coal	29	8	8	7	4	-	-	-
Natural gas	30	26	26	23	19	19	19	19
Other fossil	4	5	5	5	5	5	4	4
Hydro (w/o PSH)	6	5	5	5	6	6	6	6
Wind onshore	41	52	57	70	76	89	114	165
Wind offshore	3	6	13	22	28	34	40	46
PV	39	51	65	76	93	109	126	142
Biomass	9	9	8	6	6	6	6	6
Other renewable	-	0	0	1	1	1	2	2
Short-term storage (incl. PSH)	9	9	9	9	9	9	9	9
Reserves, DSM, Imports	-	23	35	40	51	55	55	55
Total	**204**	**209**	**234**	**268**	**297**	**333**	**381**	**455**
Total firm capacity	*121*	*99*	*99*	*99*	*99*	*99*	*99*	*99*
Electricity generation	**TWh (net)**							
Nuclear energy	87	63	-	-	-	-	-	-
Lignite	143	41	20	19	-	-	-	-
Hard coal	107	42	42	38	19	-	-	-
Natural gas	59	88	100	86	55	73	29	3
Other fossil	21	19	18	15	13	10	8	6
Hydro	19	23	23	22	22	22	22	22
Wind onshore	71	97	114	147	168	205	263	379
Wind offshore	8	28	57	96	117	148	170	195
PV	39	47	61	71	87	104	120	135
Biomass	50	43	38	26	22	23	25	12
Other renewable	0	1	3	4	6	8	10	12
Total generation	**604**	**492**	**474**	**526**	**510**	**593**	**647**	**766**
renewable share	*187*	*239*	*295*	*367*	*423*	*510*	*610*	*756*
Net electricity imports	-52	11	15	-38	-8	11	-2	-97
CO_2 emissions	**million t CO_2**							
Lignite	168	40	19	19	-	-	-	-
Hard coal	111	36	35	32	16	-	-	-
Natural gas	38	45	48	40	23	29	11	1
Other fossil	34	36	32	28	23	18	14	9
Total	**352**	**156**	**134**	**118**	**62**	**46**	**25**	**10**
Cum. CO_2 emissions	**million t CO_2**							
Lignite	168	736	884	979	1,026	1,026	1,026	1,026
Hard coal	111	445	623	790	911	952	952	952
Natural gas	38	212	443	662	818	948	1,048	1,079
Other fossil	34	211	380	529	655	756	834	892
Total	**352**	**1,603**	**2,330**	**2,961**	**3,411**	**3,682**	**3,860**	**3,948**

Table A-6
Results for scenario with plant lifetime limit of 25 years and an ambitious expansion of renewable energies, 2015–2050

Source: Calculations by Öko-Institut and Prognos

	2015	2020	2025	2030	2035	2040	2045	2050
Production capacity	GW (net)							
Nuclear energy	12	8	-	-	-	-	-	-
Lignite	21	9	6	3	3	-	-	-
Hard coal	29	8	8	8	7	4	-	-
Natural gas	30	26	26	23	19	19	19	19
Other fossil	4	5	5	5	5	5	4	4
Hydro (w/o PSH)	6	5	5	5	6	6	6	6
Wind onshore	41	52	57	70	76	89	114	165
Wind offshore	3	6	13	22	28	34	40	46
PV	39	51	65	76	93	109	126	142
Biomass	9	9	8	6	6	6	6	6
Other renewable	-	0	0	1	1	1	2	2
Short-term storage (incl. PSH)	9	9	9	9	9	9	9	9
Reserves, DSM, Imports	-	19	32	40	45	51	55	55
Total	**204**	**209**	**234**	**268**	**297**	**333**	**381**	**455**
Total firm capacity	*121*	*99*	*99*	*99*	*99*	*99*	*99*	*99*
Electricity generation	TWh (net)							
Nuclear energy	87	63	-	-	-	-	-	-
Lignite	143	63	39	20	17	-	-	-
Hard coal	107	42	38	39	27	25	-	-
Natural gas	59	78	83	87	45	58	29	3
Other fossil	21	19	17	15	13	10	8	6
Hydro	19	23	23	22	22	22	22	22
Wind onshore	71	97	114	147	168	205	263	379
Wind offshore	8	28	57	96	117	148	170	195
PV	39	47	61	71	87	104	120	135
Biomass	50	43	38	26	22	23	25	12
Other renewable	0	1	3	4	6	8	10	12
Total generation	**604**	**504**	**472**	**528**	**524**	**604**	**647**	**765**
renewable share	*187*	*239*	*295*	*367*	*423*	*510*	*610*	*756*
Net electricity imports	-52	-0	16	-40	-22	0	-1	-97
CO_2 emissions	million t CO_2							
Lignite	168	66	39	19	17	-	-	-
Hard coal	111	36	33	33	22	21	-	-
Natural gas	38	40	40	40	19	23	11	1
Other fossil	34	36	32	28	23	18	14	9
Total	**352**	**177**	**143**	**119**	**81**	**62**	**25**	**10**
Cum. CO_2 emissions	million t CO_2							
Lignite	168	753	1,015	1,160	1,250	1,292	1,292	1,292
Hard coal	111	480	652	816	955	1,063	1,116	1,116
Natural gas	38	232	433	633	779	885	971	1,001
Other fossil	34	210	377	526	651	752	830	888
Total	**352**	**1,676**	**2,477**	**3,135**	**3,635**	**3,992**	**4,208**	**4,296**

Table A-7
Results for scenario with plant lifetime limit of 30 years and an ambitious expansion of renewable energies, 2015–2050

Source: Calculations by Öko-Institut and Prognos

	2015	2020	2025	2030	2035	2040	2045	2050
Production capacity	**GW (net)**							
Nuclear energy	12	8	-	-	-	-	-	-
Lignite	21	9	9	6	3	3	-	-
Hard coal	29	11	8	8	8	7	4	-
Natural gas	30	26	26	23	19	19	19	19
Other fossil	4	5	5	5	5	5	4	4
Hydro (w/o PSH)	6	5	5	5	6	6	6	6
Wind onshore	41	52	57	70	76	89	114	165
Wind offshore	3	6	13	22	28	34	40	46
PV	39	51	65	76	93	109	126	142
Biomass	9	9	8	6	6	6	6	6
Other renewable	-	0	0	1	1	1	2	2
Short-term storage (incl. PSH)	9	9	9	9	9	9	9	9
Reserves, DSM, Imports	-	17	28	37	44	45	51	55
Total	**204**	**209**	**234**	**268**	**297**	**333**	**381**	**455**
Total firm capacity	*121*	*99*	*99*	*99*	*99*	*99*	*99*	*99*
Electricity generation	**TWh (net)**							
Nuclear energy	87	63	-	-	-	-	-	-
Lignite	143	64	61	39	17	20	-	-
Hard coal	107	52	37	34	26	39	15	-
Natural gas	59	72	73	70	37	30	16	2
Other fossil	21	19	17	15	13	10	8	6
Hydro	19	23	23	22	22	22	22	22
Wind onshore	71	97	114	147	168	205	263	379
Wind offshore	8	28	57	96	117	148	170	194
PV	39	47	61	71	87	104	120	135
Biomass	50	43	38	26	22	24	25	9
Other renewable	0	1	3	4	6	8	10	12
Total generation	**604**	**511**	**483**	**524**	**516**	**610**	**649**	**761**
renewable share	*187*	*239*	*295*	*367*	*422*	*510*	*609*	*752*
Net electricity imports	-52	-7	5	-37	-14	-5	-3	-91
CO_2 emissions	**million t CO_2**							
Lignite	168	67	64	38	17	19	-	-
Hard coal	111	47	32	30	22	33	12	-
Natural gas	38	37	36	33	16	13	6	1
Other fossil	34	35	31	28	23	18	14	9
Total	**352**	**187**	**163**	**128**	**78**	**82**	**32**	**10**
Cum. CO_2 emissions	**million t CO_2**							
Lignite	168	757	1,085	1,340	1,478	1,567	1,615	1,615
Hard coal	111	507	703	857	987	1,124	1,235	1,264
Natural gas	38	226	409	581	702	775	824	842
Other fossil	34	209	377	524	649	750	828	885
Total	**352**	**1,699**	**2,574**	**3,302**	**3,816**	**4,216**	**4,501**	**4,606**

Table A-8
Results for the Transformation Scenario with an ambitious expansion of renewable energies, 2015–2050

Source: Calculations by Öko-Institut and Prognos

	2015	2020	2025	2030	2035	2040	2045	2050
Production capacity	GW (net)							
Nuclear energy	12	8	-	-	-	-	-	-
Lignite	21	9	9	6	3	-	-	-
Hard coal	29	11	8	8	8	-	-	-
Natural gas	30	26	26	23	19	19	19	19
Other fossil	4	5	5	5	5	5	4	4
Hydro (w/o PSH)	6	5	5	5	6	6	6	6
Wind onshore	41	52	57	70	76	89	114	165
Wind offshore	3	6	13	22	28	34	40	46
PV	39	51	65	76	93	109	126	142
Biomass	9	9	8	6	6	6	6	6
Other renewable	-	0	0	1	1	1	2	2
Short-term storage (incl. PSH)	9	9	9	9	9	9	9	9
Reserves, DSM, Imports	-	17	28	37	44	55	55	55
Total	**204**	**209**	**234**	**268**	**297**	**333**	**381**	**455**
Total firm capacity	*121*	*99*	*99*	*99*	*99*	*99*	*99*	*99*
Electricity generation	TWh (net)							
Nuclear energy	87	63	-	-	-	-	-	-
Lignite	143	53	41	29	10	-	-	-
Hard coal	107	52	41	35	26	-	-	-
Natural gas	59	74	77	71	33	65	23	3
Other fossil	21	19	17	15	13	10	8	6
Hydro	19	23	23	22	22	22	22	22
Wind onshore	71	97	114	147	168	205	263	379
Wind offshore	8	28	57	96	117	148	170	195
PV	39	47	61	71	87	104	120	135
Biomass	50	43	38	26	22	23	25	10
Other renewable	0	1	3	4	6	8	10	12
Total generation	**604**	**500**	**471**	**518**	**504**	**585**	**641**	**763**
renewable share	*187*	*239*	*295*	*367*	*422*	*510*	*609*	*754*
Net electricity imports	-52	11	15	-38	-8	11	-2	-97
CO_2 emissions	million t CO_2							
Lignite	168	55	43	29	10	-	-	-
Hard coal	111	47	35	31	22	-	-	-
Natural gas	38	38	38	33	14	26	9	1
Other fossil	34	35	31	28	23	18	14	9
Total	**352**	**175**	**148**	**120**	**69**	**43**	**23**	**10**
Cum. CO_2 emissions	million t CO_2							
Lignite	168	764	1,009	1,189	1,285	1,285	1,285	1,285
Hard coal	111	474	679	844	977	977	977	977
Natural gas	38	195	383	560	679	779	867	892
Other fossil	34	211	378	526	651	751	829	887
Total	**352**	**1,643**	**2,449**	**3,119**	**3,592**	**3,793**	**3,958**	**4,041**

Annex 2: List of lignite and hard coal power plants with capacities >100 MW in the Transformation Scenario

Table A-9
Lignite power plants with capacities >100 MW in the Transformation Scenario

Source: German Federal Network Agency, calculations by Öko-Institut and Prognos

FedNetA No.	Plant name	Start-up year	Capacity	Decommissioning starts	CO_2-optimized operation from
			MW		
BNA1401a	Neurath F (BoA 2)	2012	1,050	2036	2033
BNA1401b	Neurath G (BoA 3)	2012	1,050	2036	2033
BNA0709	Niederaußem K (BoA 1)	2002	944	2033	2023
BNA0115	Lippendorf S	2000	875	2031	2021
BNA0116	Lippendorf R	1999	875	2030	2020
BNA0124	Boxberg Q	2000	857	2031	2021
BNA0914	Schwarze Pumpe A	1997	750	2028	2019
BNA0915	Schwarze Pumpe B	1998	750	2029	2019
BNA0708	Niederaußem G	1974	653	2019	-
BNA0707	Niederaußem H	1974	648	2019	-
BNA1404	Boxberg R	2012	640	2036	2033
BNA0699	Neurath D	1975	607	2019	-
BNA0700	Neurath E	1976	604	2019	-
BNA1027	Weisweiler G	1974	592	2019	-
BNA1028	Weisweiler H	1975	592	2019	-
BNA0122	Boxberg N	1979	465	2019	-
BNA0123	Boxberg P	1980	465	2019	-
BNA0785	KW Jänschwalde A	1981	465	2019	-
BNA0786	KW Jänschwalde B	1982	465	2019	-
BNA0787	KW Jänschwalde C	1984	465	2019	-
BNA0788	KW Jänschwalde D	1985	465	2019	-
BNA0878	Schkopau A	1996	450	2027	2019
BNA0879	Schkopau B	1996	450	2027	2019
BNA1025	Weisweiler E	1965	312	2019	-
BNA1026	Weisweiler F	1967	304	2019	-
BNA0705	Niederaußem D	1963	297	2020	2019
BNA0712	Niederaußem C	1965	294	2020	2019
BNA0697	Neurath B	1972	288	2019	-
BNA0696	Neurath A	1972	277	2019	-
BNA0292	Frechen/Wachtberg	1959	118	2019	-

Note: Lignite power plants transferred to the security standby are not shown.

Table A-10
Hard coal power plants with capacities >100 MW in the Transformation Scenario
Source: German Federal Network Agency, calculations by Öko-Institut and Prognos

FedNetA No.	Plant name	Start-up year	Capacity	Decommission-ing starts	CO_2-optimized operation from
			MW		
BNAP029	Datteln 4	2019*	1,055	2036	-
BNA0793	Heyden 4	1987	875	2019	-
BNA0646b	Mannheim GKM 9	2015	843	2036	-
BNA0518b	Karlsruhe RDK 8	2014	842	2036	2035
BNA0493	Ibbenbüren B	1985	794	2019	-
BNA0434	HKW Heilbronn 7	1985	778	2019	-
BNA0413c	Westfalen E	2014	765	2036	2035
BNA1558	Hamburg Moorburg B	2015	760	2036	-
BNA1673	Hamburg Moorburg A	2015	760	2036	-
BNA1508	Trianel Lünen	2013	746	2036	2034
BNA1674	Wilhelmshaven	2015	731	2036	-
BNA0216b	KW Walsum 10	2013	725	2036	2034
BNA0093	Bexbach	1983	721	2019	-
BNA0991	KW Voerde A	1982	695	2019	-
BNA0992	KW Voerde B	1985	695	2019	-
BNA1046a	Gersteinwerk K2	1984	608	2020	2019
BNA0377	Staudinger 5	1992	510	2023	2019
BNA0849	Rostock	1994	508	2025	2019
BNA0518a	Karlsruhe RDK 7	1985	505	2019	-
BNA1093	Zolling 5	1986	472	2019	-
BNA0450	Herne 4	1989	449	2020	2019
BNA0646a	Mannheim GKM 8	1993	435	2024	2019
BNA0020	HKW Altbach/Deizisau 1	1985	433	2019	-
BNA0645	Mannheim GKM 7	1982	425	2019	-
BNA0216a	Walsum 9	1988	370	2019	-
BNA0019	HKW Altbach/Deizisau 2	1997	336	2028	2019
BNA0969b	München Nord 2	1991	333	2022	2019
BNA1037	Werdohl-Elverlingsen E4	1982	310	2019	-
BNA0086	Berlin Reuter West D	1987	282	2019	-
BNA0087	Berlin Reuter West E	1988	282	2019	-
BNA0644	Mannheim GKM 6	2005	255	2036	2026
BNA0999	Völklingen-Fenne	1989	211	2020	2019
BNA0402	Hamburg Tiefstack	1993	194	2024	2019
BNA0935	Stuttgart-Münster N12	1982	179	2019	-
BNA0998	MKW Völklingen-Fenne	1982	179	2019	-
BNA1076a	HKW Wolfsburg West 1	1985	139	2019	-
BNA1076b	HKW Wolfsburg West 2	1985	139	2019	-
BNA0420	Hannover GKH 1	1989	136	2020	2019
BNA0421	Hannover GKH 2	1989	136	2020	2019
BNA0144	Bremen Hastedt 15	1989	119	2020	2019

Note: Power plants expected to shut down in the coming years are not shown. – * Own assumption

Annex 3: Assumptions for development of power plant fleets in Germany’s neighbouring countries

Table A-11

Development of power plant fleets in Austria and Switzerland, 2014–2040

Source: Calculations by Prognos based on Entso-E

	2014*	2020	2025	2030	2035	2040
	GW					
Austria						
Nuclear energy	0.0	0.0	0.0	0.0	0.0	0.0
Lignite	0.0	0.0	0.0	0.0	0.0	0.0
Hard coal	1.2	1.2	1.2	1.2	0.1	0.1
Natural gas	4.9	5.4	5.3	5.3	5.3	5.0
Petroleum	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.0	0.0	0.0	0.0
Other fossil	1.3	1.7	1.6	1.6	1.6	1.6
Pumped storage	0.0	4.0	4.0	4.0	4.0	4.0
Hydro (w/o PSH)	13.6	11.3	12.6	13.8	13.8	13.8
Biomass	0.6	1.4	1.6	1.8	1.9	2.0
Wind onshore	2.1	3.4	4.4	5.5	6.6	7.7
Wind offshore	0.0	0.0	0.0	0.0	0.0	0.0
Solar (PV)	0.6	2.9	4.7	6.5	8.1	9.8
Other renewable	0.0	0.0	0.0	0.0	0.0	0.0
Demand management	0.0	0.2	0.2	0.5	0.6	0.6
Switzerland						
Nuclear energy	3.2	2.2	1.2	0.0	0.0	0.0
Lignite	0.0	0.0	0.0	0.0	0.0	0.0
Hard coal	0.0	0.0	0.0	0.0	0.0	0.0
Natural gas	0.1	1.4	2.8	5.3	7.8	7.7
Petroleum	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.0	0.0	0.0	0.0
Other fossil	0.5	0.4	0.4	0.4	0.4	0.4
Pumped storage	0.0	0.0	0.7	0.7	0.7	0.7
Hydro (w/o PSH)	14.0	12.1	12.1	12.2	12.2	12.2
Biomass	0.0	0.5	0.9	1.3	1.4	1.5
Wind onshore	0.1	0.4	0.6	0.9	1.1	1.3
Wind offshore	0.0	0.0	0.0	0.0	0.0	0.0
Solar (PV)	0.7	2.4	3.4	4.5	5.6	6.8
Other renewable	0.0	0.0	0.0	0.0	0.0	0.0
Demand management	0.0	1.2	1.4	1.6	1.9	2.2

Notes: *for 2014: Hydro power plants include pumped storage (PSH), Sweden and Norway data includes peat, no historical data available for demand management

Table A-12
Development of power plant fleets in France, Luxembourg and Belgium, 2014–2040
Source: Calculations by Prognos based on Entso-E

	2014*	2020	2025	2030	2035	2040
	GW					
France & Luxembourg						
Nuclear energy	63.1	63.1	44.2	21.3	8.6	6.0
Lignite	0.0	0.0	0.0	0.0	0.0	0.0
Hard coal	5.2	3.5	3.5	1.8	0.7	0.5
Natural gas	6.3	16.1	34.9	48.4	57.3	63.0
Petroleum	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.0	0.0	0.0	0.0
Other fossil	12.0	7.5	4.7	4.3	4.3	4.1
Pumped storage	0.0	5.6	5.6	5.6	5.6	5.6
Hydro (w/o PSH)	26.3	19.4	20.3	21.1	21.1	21.1
Biomass	1.5	4.0	6.7	9.4	10.1	10.8
Wind onshore	9.0	20.0	29.1	38.2	46.8	55.4
Wind offshore	0.0	5.4	9.9	14.4	16.9	19.4
Solar (PV)	5.1	22.2	35.9	49.6	62.0	74.4
Other renewable	0.0	0.0	0.0	0.0	0.0	0.0
Demand management	0.0	7.1	7.3	8.2	9.4	9.4
Belgium						
Nuclear energy	5.9	4.0	4.0	0.0	0.0	0.0
Lignite	0.0	0.0	0.0	0.0	0.0	0.0
Hard coal	0.0	0.3	0.0	0.0	0.0	0.0
Natural gas	6.9	7.6	7.8	8.7	11.9	12.6
Petroleum	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.0	0.0	0.0	0.0
Other fossil	0.2	2.3	2.3	2.3	2.3	1.5
Pumped storage	0.0	1.2	1.2	1.2	1.2	1.2
Hydro (w/o PSH)	1.4	0.1	0.1	0.1	0.1	0.1
Biomass	1.3	1.3	1.8	2.3	2.5	2.6
Wind onshore	1.1	2.8	4.1	5.4	6.4	7.5
Wind offshore	0.6	1.9	3.0	4.0	5.0	5.9
Solar (PV)	2.7	4.4	5.6	6.7	8.4	10.1
Other renewable	0.0	0.0	0.0	0.0	0.0	0.0
Demand management	0.0	1.0	1.0	1.1	1.2	1.2

Notes: * for 2014: Hydro power plants include pumped storage (PSH), Sweden and Norway data includes peat, no historical data available for demand management

Table A-13
Development of power plant fleets in the Netherlands and Denmark, 2014–2040
Source: Calculations by Prognos based on Entso-E

	2014*	2020	2025	2030	2035	2040
	GW					
Netherlands						
Nuclear energy	0.5	0.0	0.0	0.0	0.0	0.0
Lignite	0.0	0.0	0.0	0.0	0.0	0.0
Hard coal	5.7	5.5	5.5	4.9	4.5	3.9
Natural gas	20.1	16.3	13.8	13.6	13.0	13.4
Petroleum	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.0	0.0	0.0	0.0
Other fossil	1.7	1.3	1.3	1.3	1.3	1.3
Pumped storage	0.0	0.0	0.0	0.0	0.0	0.0
Hydro (w/o PSH)	0.0	0.1	0.1	0.2	0.2	0.2
Biomass	0.4	1.4	2.2	2.9	3.1	3.3
Wind onshore	2.5	3.9	4.9	6.0	7.2	8.4
Wind offshore	0.2	2.7	4.8	6.8	8.4	10.0
Solar (PV)	0.8	4.1	6.6	9.1	11.4	13.7
Other renewable	0.0	0.0	0.0	0.0	0.0	0.0
Demand management	0.0	0.8	0.8	1.1	1.1	1.1
Denmark						
Nuclear energy	0.0	0.0	0.0	0.0	0.0	0.0
Lignite	0.0	0.0	0.0	0.0	0.0	0.0
Hard coal	2.7	2.9	2.6	2.0	1.3	0.4
Natural gas	2.2	3.0	0.2	0.1	0.6	0.6
Petroleum	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.0	0.0	0.0	0.0
Other fossil	0.1	1.1	0.8	0.8	0.8	0.8
Pumped storage	0.0	0.0	0.0	0.0	0.0	0.0
Hydro (w/o PSH)	0.0	0.0	0.0	0.0	0.0	0.0
Biomass	1.4	2.2	3.2	4.1	4.5	4.8
Wind onshore	3.5	4.5	5.2	5.9	7.3	8.7
Wind offshore	1.3	2.9	4.2	5.5	6.5	7.5
Solar (PV)	0.6	1.7	2.5	3.4	4.3	5.1
Other renewable	0.0	0.0	0.0	0.0	0.0	0.0
Demand management	0.0	0.9	0.9	0.9	0.9	0.9

Notes: *for 2014: Hydro power plants include pumped storage (PSH), Sweden and Norway data includes peat, no historical data available for demand management

Table A-14
Development of power plant fleets in Sweden, Norway and Poland, 2014–2040
Source: Calculations by Prognos based on Entso-E

	2014*	2020	2025	2030	2035	2040
	GW					
Sweden & Norway						
Nuclear energy	9.9	7.3	5.5	0.0	0.0	0.0
Lignite	0.1	0.1	0.0	0.0	0.0	0.0
Hard coal	0.0	0.2	0.2	0.2	0.2	0.1
Natural gas	2.1	2.6	2.6	2.2	1.8	1.8
Petroleum	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.0	0.0	0.0	0.0
Other fossil	4.7	3.6	3.3	3.2	3.2	2.9
Pumped storage	0.0	0.4	0.4	0.4	0.4	0.4
Hydro (w/o PSH)	47.2	48.1	50.7	53.4	53.4	53.4
Biomass	3.2	4.7	5.0	5.3	5.7	6.1
Wind onshore	4.6	10.7	14.9	19.0	22.8	26.6
Wind offshore	0.2	4.4	7.9	11.4	13.1	14.8
Solar (PV)	0.0	0.4	0.7	1.0	1.3	1.5
Other renewable	0.0	0.0	0.0	0.0	0.0	0.0
Demand management	0.0	1.9	1.9	3.7	3.7	3.7
Poland						
Nuclear energy	0.0	0.0	0.0	0.0	0.0	0.0
Lignite	8.6	7.2	6.6	6.6	4.2	2.4
Hard coal	19.8	19.7	14.2	11.9	11.2	10.5
Natural gas	0.9	6.7	6.9	8.3	10.5	12.1
Petroleum	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.0	0.0	0.0	0.0
Other fossil	0.0	1.0	0.9	0.9	0.9	0.9
Pumped storage	0.0	1.4	1.4	1.4	1.4	1.4
Hydro (w/o PSH)	2.4	1.1	1.2	1.3	1.3	1.4
Biomass	0.7	1.4	1.9	2.4	2.6	2.8
Wind onshore	3.4	5.1	6.2	7.3	8.8	10.2
Wind offshore	0.0	3.1	5.7	8.3	9.8	11.2
Solar (PV)	0.0	2.0	3.7	5.3	6.6	8.0
Other renewable	0.0	0.0	0.0	0.0	0.0	0.0
Demand management	0.0	0.8	1.0	1.1	1.4	1.5

Notes: *for 2014: Hydro power plants include pumped storage (PSH), Sweden and Norway data includes peat, no historical data available for demand management

Table A-15
Development of power plant fleets in the Czech Republic, 2014–2040
Source: Calculations by Prognos based on Entso-E

	2014*	2020	2025	2030	2035	2040
	GW					
Tschechien						
Nuclear energy	3.7	3.8	3.8	3.3	1.9	1.9
Lignite	7.6	5.8	5.1	2.9	2.4	2.4
Hard coal	1.3	1.2	1.2	1.0	0.8	0.8
Natural gas	1.4	2.4	3.4	7.4	10.4	11.5
Petroleum	0.0	0.0	0.0	0.0	0.0	0.0
Waste	0.0	0.0	0.0	0.0	0.0	0.0
Other fossil	0.1	0.2	0.2	0.2	0.2	0.2
Pumped storage	0.0	1.1	1.1	1.1	1.1	1.1
Hydro (w/o PSH)	2.2	0.8	0.5	0.3	0.7	1.1
Biomass	0.4	0.7	0.6	0.6	0.7	0.8
Wind onshore	0.3	0.5	0.7	0.9	1.0	1.2
Wind offshore	0.0	0.0	0.0	0.0	0.0	0.0
Solar (PV)	2.2	2.7	3.1	3.6	4.5	5.4
Other renewable	0.0	0.0	0.0	0.0	0.0	0.0
Demand management	0.0	1.4	1.4	1.4	1.4	1.4

Notes: *for 2014: Hydro power plants include pumped storage (PSH), Sweden and Norway data includes peat, no historical data available for demand management

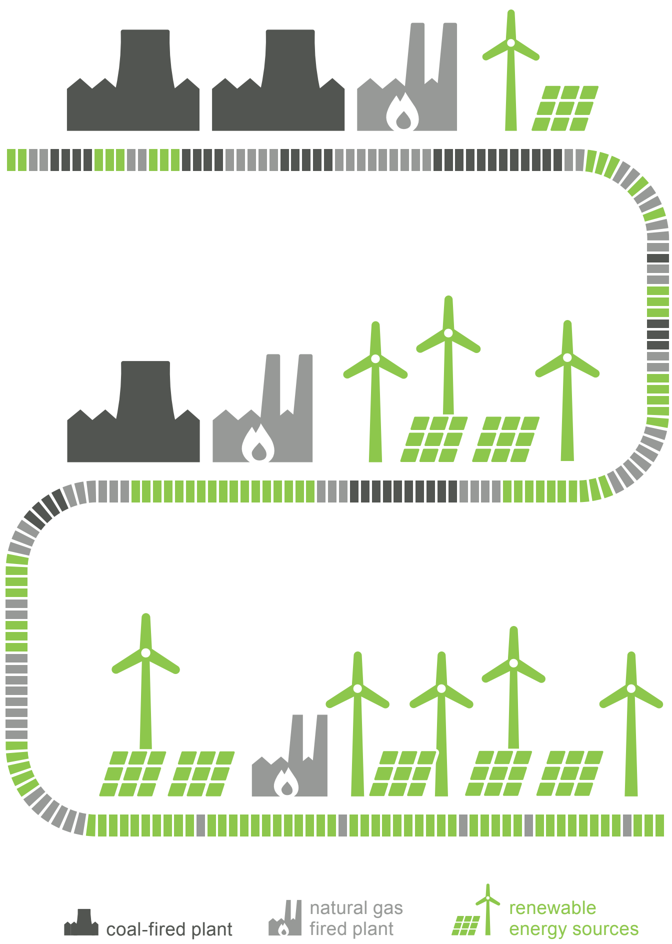
GERMANY'S ELECTRIC FUTURE
COAL PHASE-OUT 2035

2015 PARIS AGREEMENT

LIMIT GLOBAL WARMING to well below 2 °C

GLOBAL CO_2 BUDGET max. 890 Gigatons CO_2

CO_2 BUDGET GERMANY = 10 Gigatons CO_2 > ELECTRICITY SECTOR = 4 Gigatons CO_2



2015

80 % of CO_2-EMISSIONS

in the electricity sector come from lignite and hard coal plants

→ 280 of 352 Mio. t CO_2

2019

DECOMMISSIONING

of the oldest coal plants starts

- Maximum operating life for each plant is 30 years.
- between 21st and 30th year of opration yearly emissions limited to 3,35 kg CO_2/kW.

2035

PHASE-OUT COMPLETED

all coal plants decommissioned

THIS REQUIRES: The accelerated phase-out of coal.
The scaled up deployment of renewable energy sources.

www.zukunft-stromsystem.de/#en | Source: Öko-Institut/Prognos (2017): „Germany's Electric Future. Coal Phase-out 2035" for WWF Germany

100%
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Why we are here
To stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature.

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