GERMANY'S ELECTRIC FUTURE II

Regionalization of renewable power generation

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Foreword

Germany was once THE land of energy transition. Several years of standstill in climate policy have passed since then. But Germany can once again become the country of successful, accepted and eco-friendly energy transition. The key to this has always been the way we generate our electricity: we have to make coal-fired power generation a thing of the past so that renewables can be our future. Only in this way can we preserve the foundations of our life and ensure our competitiveness at the same time. Fossil energy sources are not only fuelling the climate crisis; even from a purely economic point of view, wind and solar power have long outstripped them. Renewable energies are cheaper and create more jobs: in Germany 340,000 jobs have been created in the renewable energy industry compared to approx. 20,000 jobs that remain in the coal industry. Time, then, to finally complete the political turnaround.

The path for the coal phase-out will be decided during this legislative period. WWF has mapped out a path for this. In the first part of our study, "Germany's electric future: Coal phase-out 2035", published in 2017, we showed how Germany can make a fair contribution to international climate protection in a socially acceptable and economically feasible way. To achieve this, a large share of coal-fired power generation must be terminated in the next few years by shutting down the oldest and most polluting power plants. The remainder will be phased out by 2035.

In this second part of our study on the future of Germany's electricity system, we are tackling the next step: How can the necessary expansion of renewable energies succeed? How much wind and solar energy do we need – and where in Germany can the power plants be built? Together with Öko-Institut and Prognos, we have compared the renewable electricity demand for the coming decades with available land in Germany.

But "available" does not mean free of conflict. Both the interests of local people and nature conservation concerns must be more effectively taken into account in the expansion of renewable energies than has hitherto been the case. In addition to data on capacities and land use needs, important results of the present study therefore concern planning aspects of renewable energy expansion. Without the development of better control instruments and clear rules for balancing the relevant impacts, further expansion of renewable energies would not be viable – especially as regards wind energy. This is because wind and solar power differ from coal not only in terms of their CO_2 emissions. They should and can also differ from it when it comes to environmental benefits and the participation and acceptance of citizens.

Jörg-Andreas Krüger
Chief Conservation Officer, WWF Germany

WWF'S DEMANDS
for the expansion of renewable power generation

Background

The consistent fight against global warming is the task of our time. Germany will only be able to maintain its role as a leading economic nation and high-tech location if energy transition and the transformation to a climate-neutral and sustainable economy and society are successful. In addition to phasing out fossil fuels, the expansion of renewable energies remains the key element of a successful strategy for modernization, decarbonization and transition to a fully renewable energy supply nationwide.

In 2017, WWF published the study "Germany's electric future: Coal phase-out 2035", which showed how Germany can make a fair contribution to global climate protection efforts in accordance with the Paris Agreement. The latter aims to limit global warming to well below 2°C, and if possible to 1.5°C, compared to pre-industrial levels.

Emissions from coal must therefore be halved during this legislative period and the phase-out of coal-fired power generation must be completed by the end of 2035 at the latest so that the German electricity sector stays within its remaining CO_2 budget of 4 gigatonnes. The coal phase-out could be implemented by shutting down all coal-fired power plants with an operating age of more than 30 years and by setting an annual emissions budget based on specific emissions of 3.35 t CO_2/kW for remaining power plants on the market. Emission reductions of the same magnitude could be achieved by 2020 by introducing a regional carbon floor price of € 25/t CO_2 combined with the shutdown of 7 GW from lignite-fired power plants.

Approx. 340,000 people are employed in Germany's renewable energy sector today; it has created an average of 14,000 new jobs each year since 2000. Currently there are more companies in the German renewable energy sector (approx. 34,600) than there are jobs in the German coal industry. The hugely accelerated expansion of renewable energies is not only, therefore, the foundation of future prosperity – it also has considerable industrial and political importance. It requires a clear political commitment to a forward-looking economic policy and to more climate protection in order to ensure long-term planning and investment security within the German economy.

The expansion of renewable energies opens up enormous opportunities and poses major challenges at the same time. The success of energy transition also decisively depends on the following two factors: whether renewable energies are expanded in a way that is compatible with people and nature, and whether affected citizens are able to participate appropriately and at an early stage in planning and approval processes and are included in a fair distribution of the welfare effects of a comprehensive transformation of the electricity supply system.

Energy transition has reached a very critical point in Germany. The end of coal-fired power generation has been laid down in the German government's Coalition Agreement; the when and how of the phase-out are still open. At the same time, despite enormous cost degression in recent years, the expansion of renewable energies is threatened with disruption. Not even the special tenders for 2020 announced by the governing parties in the 2018 Coalition Agreement have been implemented, even though there is no time to lose in restructuring the electricity system to one based completely on renewable energies.

In the WWF study "Germany's electric future II – Regionalization of renewable power generation", Öko-Institut and Prognos analyze how much onshore wind energy and photovoltaics are additionally needed to make electricity generation based entirely on renewables by 2050.
Its findings show that, despite the enormous pressure to act, there are diverse options available for expanding renewables. For example, there are different options for land use in view of regionalization and the renewable technology mix. There are also diverse options available for the design of flexibility options and the expansion of grid infrastructure.

The study, for which intensive modelling was carried out, shows that there is sufficient land available for the eco-compatible implementation of electricity generation based on renewable energies. Depending on the technology mix and on regionalization, the expansion of onshore wind energy and photovoltaics uses an average of up to 2.5% of Germany's surface land area.

In the accompanying study "Regional impacts of wind power expansion on bird life", Bosch & Partner validate the calculations by Öko-Institut and Prognos on the land use of onshore wind energy in Germany. Bosch & Partner adopted a bottom-up approach to assessing the impact of wind power expansion on selected bird species beyond the bounds of conservation areas. For this purpose, six districts in Germany were selected in which three bird species sensitive to wind energy – the common buzzard, the red kite and the lapwing – are found and for which a relatively high land use of wind power plants is expected.

Although only a small portion of the potential land area in Germany is considered, Bosch & Partner show that even in districts for which an above-average expansion of wind power is expected, appropriate land can be identified for this expansion that does not involve the risk of very high conflict with nature conservation concerns. In half the districts examined, it can be assumed that the required land has a medium risk of conflict and that these risks can be further reduced within regional and approval planning processes. In two other districts, the required land has only a very low or a low risk of conflict; in another district, it would only be possible to implement the expansion if areas with a high conflict risk are also incorporated.

In summary, on the basis of these results it can be assumed that land use for the conversion of wind energy to electricity is compatible with nature, even in regions with a particularly high potential for expansion, although it would not be possible to realize this potential everywhere without any risk of conflict. Additionally, the continuous development and improvement of planning elements, strategic site selection, and comprehensive assessments of land availability are necessary. Only then can conflicts be minimized from the outset and the existing impacts and yields from energy generation distributed more fairly.

To make expansion of renewable generation technologies with a relatively high land use (onshore wind energy, ground-mounted PV) as conflict-free as possible, topographical characteristics should be given much more attention in the development of transformation scenarios and strategies for energy policy. Politicians, in particular, have an obligation to create a robust foundation for planning procedures.

The major challenges to achieving a widely socially supported and eco-compatible expansion of renewable energies (particularly onshore wind power) must be tackled immediately. Only then can the coal phase-out be successfully flanked with an accelerated expansion of renewable energies, and the transformation of the electricity supply system be advanced in line with the obligations under the Paris Agreement and in a way that is compatible with people and nature.

WWF's demands

Having evaluated the study's findings, WWF Germany regards the following actions as necessary:

Expansion of renewable energies needs to be drastically accelerated and special tenders implemented

WWF calls for electricity generation from renewable energies to be doubled within the next decade. By 2030, approx. 400 terawatt hours (TWh) must be generated annually from renewable energies. This would correspond to a share of approx. 80% of gross electricity generation, of which about 350 TWh would come from two variable renewable energy sources: wind power and photovoltaics.

This necessitates a return to the minimum expansion of 2,500 MW (net) per year for onshore wind energy and photovoltaics respectively, as defined in the German Renewable Energy Sources Act (EEG) of 2014. It also requires the guarantee that renewable energies will be continuously expanded. The special tenders announced in the Coalition Agreement must be implemented immediately. It must also be ensured that an increase in renewable energies without EEG support cannot be counted towards the minimum expansion quantities of the EEG.

Planning instruments need to be strengthened

The necessary expansion of renewable energies will require even more land use than previously. Thus, it will directly influence nature, the landscape, and the direct living environment of many people. Competition of different types of land use will also intensify.

In order to reduce conflicts from the outset, the development and strengthening of coordinated spatial planning elements, strategic site selection and comprehensive assessments of land availability are necessary on national and state level. Existing instruments and practices for eco-compatible planning of onshore wind energy expansion must therefore be augmented in order to ensure an acceptable increase in renewables (particularly onshore wind energy).

It is the task of politicians and authorities to map and link the development of energy policy scenarios for expanding renewables and grid infrastructure with topographical characteristics and nature conservation concerns on site. In so doing, conflict risks can be identified in a timely manner and reduced as far as possible by planning processes.

Binding inclusion of existing spatial impacts in approval planning

Energy generation takes place in areas that are already affected – in some cases heavily – by other uses (e.g. intensive agriculture, infrastructure). Basic ecological functions are, therefore, already impaired. It should be mandatory to include the cumulative effects of these existing impacts in regional planning, the designation of suitable sites for wind energy, and the approval procedures for power plants. The aim should be to preserve or restore basic ecological functions. This requires legal and planning instruments to be developed which incorporate the cumulative impacts of areas and options for reducing impacts by other land users in approval procedures for wind power and PV.

Reliable data needed on land availability

Transparent and comprehensible spatial data must be made available to enable differentiated discussion of the complex interdependencies of different options for renewable power supply. This is not yet the case. In future, discussions should be based on publicly available, high-resolution data on land availability. In order to model the power system and infrastructure and to develop strategies, the German government must create a robust data basis which allows realistic and comprehensive consideration and classification of land restrictions.

Onshore wind power must be increased and a consistent planning and permitting framework introduced nationwide

Onshore wind power is the driving force behind energy transition. It will remain the most important renewable energy technology in the future. Today, approx. 30,000 wind power plants with a total installed capacity of 56.1 GW generate 18.8% of Germany's net electricity production. By 2050, the installed capacity of onshore wind energy – depending on the technology mix – needs to be increased by a factor of 3 to 4 compared to current levels.

Given the manifold conflicts, current approval procedures must be critically reviewed with a view to nature conservation concerns and citizen acceptance in order to increase planning and investment security in project development. To accelerate wind power expansion and to ensure its compatibility with nature and humankind, a uniform framework for wind energy expansion needs to be created nationwide and combined with consistent application of species and nature conservation legislation.

These framework conditions could, for example, comprise better coordinated regional planning and uniform national procedures for designating suitable sites for wind energy. The legal framework for concrete approval planning must be widened so that existing impacts on the landscape are included in planning decisions. The designation of suitable sites for wind energy in regional planning must not, however, replace individual assessments.

Regionalization of wind energy should be even

The transition to renewable energy tenders enacted by the German Renewable Energy Sources Act (EEG) of 2017 has increased the concentration of onshore wind energy at high-yield locations in northern Germany and led to inland locations in the south of the country being disadvantaged. It should, nevertheless, be ensured that suitable sites in less windy German states with less favourable conditions for wind power can be used. This would enable long-term expansion targets to be achieved and grid expansion needs to be limited. It also takes into account that available land in previously favourable areas is becoming scarcer.

To make regionalization of renewable energy expansion as even as possible, especially with regard to onshore wind power, the expansion of wind energy should also be promoted in southern Germany, e.g. by introducing a regional quota (southern quota) in the tendering procedure.

Expansion of photovoltaics needs to be strengthened

By extensively exploiting potentials for roof-mounted photovoltaic (PV) systems and, to a lesser extent, ground-mounted PV systems (*solar focus* scenario), the land use of onshore wind energy can be reduced by up to one third compared to a conventional development path (*energy transition reference* scenario). The expansion of photovoltaics (especially roof-mounted PV) in conjunction with the use of battery storage systems is thus a sensible overarching strategy – especially with a view to land efficiency – and should constitute a central element of any future strategy for expanding renewable energies.

Regulatory barriers to PV and battery storage need to be removed

As expansion of PV and battery storage systems depends decisively on the investment behaviour of home-owners, appropriate economic incentives must be created and regulatory barriers removed. It should also be examined whether other instruments could be implemented, e.g. introducing an obligation for a PV system to be installed and maintained on new buildings and – if feasible – when structural changes are made to the roof. This only makes sense, however, if their operation is economically attractive.

WWF therefore calls on the German government to strengthen tenant power models and to abolish the existing unequal treatment of own consumption based on renewable energies and tenant power consumption so that energy transition can move into the cities. It is also important to remove regulatory barriers to profitable operation of battery storage systems.

Improving citizen participation in project planning and financial inclusion

For the social project of energy transition to succeed, it is imperative to maintain a high degree of social support and to promote the acceptance of wind energy projects in particular. Acceptance should not be seen as a direct consequence of public participation and the financial inclusion of citizens. Rather, it should be conceived as the result of an early and transparent participation process and perceived distributive justice. With this in mind, it is necessary to facilitate the early and transparent participation of local citizens in the planning process and to enable their appropriate financial inclusion in the added value of wind energy projects.

Grid expansion needs to be accelerated and long-term needs in different technological scenarios calculated

The “starting grid” and grid expansion needs specified in Germany’s Grid Development Plan for 2030 should be implemented as quickly as possible, irrespective of regionalization and the technology mix of renewable energies. Overall there is only a very small difference in the expansion and investment volumes as a result of the technology mix and regionalization.

By contrast, from the mid-2030s onwards, path dependencies and different grid infrastructure needs are to be expected due to the technology mix and regionalization, which must be taken into account at an early stage. In view of the long-term planning procedures, eco-compatible implementation and public participation, key planning decisions need to be taken early in order to avoid cost-intensive corrections of path dependencies.

In order to map these path dependencies appropriately and robustly, grid development scenarios must have a far broader spread, i.e. more differentiated mapping is needed of possible regional and technological development paths for renewable power generation and own-consumption systems. Land restrictions must be considered in the future modelling of transmission system operators. The scenario framework of grid development plans must include at least two long-term scenarios with a time horizon of 2050.

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Executive Summary

The German electricity sector is of paramount importance to both energy and climate policy. In 2017, the share of electricity sector emissions in the total greenhouse gas emissions (taking into account non-CO_2 greenhouse gases and international air transport emissions for fuel quantities fuelled in Germany) amounted to approx. 35.5%. This makes the electricity sector the largest single contributor by far to Germany's greenhouse gas emission balance. In view of the German and international climate targets, the electricity sector has made an insufficient contribution to emission reductions since 1990.

Germany's electricity sector also faces a threefold challenge in meeting the goals of the Paris Agreement adopted in 2015, which aim to forestall serious consequences of global climate change for nature and human society.

Firstly, coal-fired power plants with their especially high greenhouse gas (GHG) emissions must be removed from Germany's electricity system in the short and medium term. In the medium and long term, fossil-fuelled power generation that is less carbon-intensive (e.g. natural gas power plants) must also be replaced. Subject to the German electricity sector having a fair share of the remaining global emissions budget, large coal-fired power plant capacities are shut down in the relatively short term; coal-fired power generation in Germany is completely phased out by the end of 2035. Compared to current levels, coal-fired power generation in Germany would thus be reduced by 64% by 2025 and by 73% by 2030. It would be completely phased out by the end of 2035.

Secondly, more electricity will have to be produced in future than at present. The electrification of the transport and heat sectors can and must make a substantial contribution to the necessary reductions in GHG emissions. Thus, despite considerable efficiency gains in traditional electricity applications, electricity demand will be the same level again in 2035 that it is today; in 2050, it will be almost 30% above current levels.

Thirdly, electricity generation plants based on renewable energies must be built to substitute the phased-out capacities of fossil-based electricity generation and to meet the electricity demand which is projected to increase in future. The current net electricity generation based on renewable energies will have to be increased from 218 billion kilowatt hours (218 terawatt hours – TWh) today by approx. 85% to approx. 400 TWh in 2030, by 110% to 460 TWh in 2035 and by 250% to over 700 TWh in 2050. The growth of electricity generation based on renewable energies is driven by the most cost-effective onshore wind power plants, offshore wind power plants and solar power plants (photovoltaics – PV).

The transition to an electricity system based predominantly on onshore and offshore wind power and PV creates new challenges. Renewable electricity generation will be much more widely distributed; and depends on the availability of wind and solar energy, which is variable and differs from region to region. This necessitates stronger and better integrated grid infrastructures; storage and other flexibility options (flexible demand, backup power plants, etc.) are also needed in the long term. Thus, alongside the traditional cost issues, restrictions resulting from the land use of the new energy system and from the need to redesign and strengthen grid infrastructures gain in significance.

There are different designs for how the renewable electricity system can be developed. The costs and land use and, if applicable, the infrastructure needs of these different system designs originate not only in the specific costs and the specific land demand of the various power generation options based on renewable energies. If certain electricity system variants involve a higher storage demand, more renewable electricity may have to be generated due to the generation patterns and storage losses. If fewer high-yield sites have to be used due to land restrictions, the demand for installed power plant capacity likewise increases. Both entail higher costs, a higher need for available land and changed infrastructure needs.

Two scenarios for the development of the German electricity system were developed and analyzed in detail in order to assess these complex interrelationships: an *energy transition reference* scenario and a *solar focus* scenario.

The ***energy transition reference*** **scenario** comprises a development presented in most of the latest research on the transformation of the German electricity system. The expansion of renewable energies in the electricity sector is focused on onshore wind energy in this scenario.

» **In 2030,** 163 TWh are generated from onshore wind energy, 107 TWh from offshore wind power energy and 79 TWh from photovoltaics. This corresponds to an increase of 2017 levels by a factor of 1.8, 6.0 and 2.0 respectively. Generation capacities of 80 GW for onshore wind power, 27 GW for offshore wind power and 87 GW for PV must have been installed by then. In 2030, 75% of the total PV capacity takes the form of roof-mounted systems; the remaining 25% are ground-mounted systems.

» **In 2035,** 186 TWh are generated by onshore wind power plants, 133 TWh by offshore wind power plants and 94 TWh by PV systems. Compared to 2017, this corresponds to an increase by a factor of 2.1, 7.4 and 2.4 respectively. To achieve this, generation capacities amounting to 87 GW for onshore wind power, 33 GW for offshore wind power and 105 GW for PV must be available in the electricity system. In 2030, 75% of the total PV capacity is attributable to roof-mounted systems and 25% to ground-mounted systems.

» **In 2050,** onshore wind power plants generate 388 TWh, offshore wind power plants 185 TWh and PV systems 141 TWh. Compared to 2017 levels, this corresponds to an increase by a factor of 4.4, 10.3 and 3.5 respectively. The generation capacities needed for this are 178 GW for onshore wind power, 51 GW for offshore wind power and 154 GW for PV. In 2050, 69% of PV systems are roof-mounted and 31% are ground-mounted.

The development in the *energy transition reference* is compared to that in the ***solar focus* scenario**. The latter scenario involves a very extensive exploitation of the potentials for roof-mounted PV systems. It also assumes a very high proportion of self-consumption for PV, with the result that grid-based electricity purchases are minimized for these customer groups.

» **In 2030,** 135 TWh of electricity are generated by onshore wind power plants, 108 TWh by offshore wind power plants and 107 TWh by PV systems. Compared to 2017, this corresponds to an increase by a factor of 1.5, 6.0 and 2.7 respectively. To achieve this, generation capacities amounting to 67 GW for onshore wind power, 27 GW for offshore wind power and 116 GW for PV must have been installed. In 2030 roof-mounted systems account for 71% of total PV capacity in this scenario.

» **In 2035,** 137 TWh of electricity are generated by onshore wind power plants, 133 TWh by offshore wind power plants and 147 TWh by PV systems. Based on 2017 levels, this corresponds to an increase by a factor of 1.5, 7.4 and 3.7 respectively. This necessitates a generation capacity of 67 GW from onshore wind power plants[1], 33 GW from offshore wind power plants and 151 GW from PV systems. Roof-mounted systems account for 69% of the total PV capacity in 2035.

» **In 2050,** onshore wind power plants generate 231 TWh of electricity, offshore wind power plants 189 TWh and PV systems 288 TWh. Compared to 2017, this represents an increase by a factor of 2.6, 10.5 and 7.2 respectively. This necessitates capacities of 115 GW for onshore wind power, 51 GW for offshore wind power plants and 313 GW for PV systems. In 2050, 67% of the total PV capacity is attributable to roof-mounted systems, with the result that the potentials for roof-mounted PV are almost completely exhausted in 2050.

1 The increased power generation from the same installed capacity in 2035 compared to 2030 stems from improvements to power plant efficiency through repowering.

The land use of onshore wind power plants and ground-mounted PV systems as well as their regional distribution are based on district-specific analyses of the areas concerned. First of all, human settlements and transport infrastructure areas, peatland and heathland, woodland, water areas and mining areas were excluded from use for renewable power generation. The resulting available land was then further limited to allow for minimum distances from the above-mentioned areas. Considering Germany as a whole, an average of approx. 95% of land area is excluded from the construction of wind and ground-mounted PV systems. This share varies widely across the different federal states *(Bundesländer)* and districts *(Landkreise)*.

With regard to the land available for wind and solar power generation overall, the largest available area potentials are in Schleswig-Holstein, Mecklenburg-West Pomerania and Saxony-Anhalt, where on average 6.1% to 6.9% of the total area in the state was identified as available for renewable power generation. Based on the absolute area size of the different federal states, the largest areas for renewable power generation from wind and solar energy are available in Bavaria, Lower Saxony and North Rhine-Westphalia.

The share of land per district that in principle allows for electricity generation from wind power and ground-mounted PV systems under the approach used in this study ranges between 0.4% and 8.2%. For the 10 districts with the lowest area potentials for these uses, the area-weighted share amounts to 0.9%; for the 10 districts with the highest area potentials, it amounts to 7.6%.

Compared with other studies, the area potentials calculated in this study are at the lower end of the range (an analysis by the German Federal Environment Agency assumes that a 13.8% share of land in Germany is basically available for onshore wind power (UBA, 2013)). Other studies, however, apply staggered levels of land use restrictions, which result in lower values for areas that are mostly free of restrictions. In the case of a higher land demand, land with soft restrictions (spatial effects, pollution level due to other land use) may also have to be used, which necessitates case-by-case assessments of competition for land. In both scenarios, therefore, the land use for onshore wind power and for ground-mounted PV systems are compared with the land restrictions assumed in the most conservative estimates of other studies.

The present study conducts a district-specific analysis based on the identified available land on the basis of which electricity generation from wind power and PV could be expanded. In comparison to the above-mentioned analyses that consider various land use restrictions in detail and in a particularly restrictive way (taking into account distances to human settlements and nature and species conservation), this analysis generates values for area demand that also fall within the range of available land that is mostly free of restrictions, even when a very conservative approach is applied (up to 0.9% of the total land). In the *energy transition reference* scenario, the average land use amounts to 0.2% for ground-mounted PV; and in the *solar focus* scenario, the land use corresponds to approx. 0.5% of Germany's total surface area.

Due to the more restrictive assumptions, however, onshore wind power may lead to a strained situation regarding land use. After 2045, land use reaches 1.7% nationally in the *energy transition reference* scenario which, considered separately and totaled, can be regarded as mostly free of restrictions even from a conservative perspective. In 2050, land use increases to 2.3% due to onshore wind energy, which exceeds the conservative estimate of available land that is mostly free of restrictions. It does, however, fall within the range of the available land for which soft restrictions apply in conservative estimates. In the *solar focus* scenario, the most conservative estimate of land mostly free of restrictions (1.7%) is not completely tapped (by approx. 0.2 percentage points) in 2050; it is approx. one third below the percentage determined in the *energy transition reference* scenario.

From an overall perceptive, then, both scenarios are compatible with real land availability potentials. In the *energy transition reference* scenario, it is more likely that land restrictions can become relevant, at least in specific regions. Overall, however, such restrictions only become relevant on a larger scale after 2030; in some districts this may occur earlier.

For the transition to an electricity system that is extensively based on renewable energies that depend on wind and solar availability, there is a substantial demand for system integration options ("flexibility options"). The different emphases of the two scenarios bring about different patterns in this respect.

The first flexibility option is cross-border electricity imports and exports with neighbouring countries or on the European electricity market. During peaks of generation from renewable energy in future, electricity could be exported; during periods of low generation from renewable energies, electricity can be imported from other countries:

- In the *energy transition reference* scenario, Germany's electricity net import-export balance amounts to 35 TWh (exports) in 2030, 36 TWh (exports) in 2035 and 97 TWh (exports) in 2050.

- In the *solar focus* scenario, Germany's electricity net import-export balance amounts to 35 TWh (exports) in 2030, after which the values are similar to those in the *energy transition reference* scenario, amounting to 39 TWh (exports) in 2035 and 92 TWh (exports) in 2050.

The second flexibility option is short-term electricity storage, most notably battery electric storage systems. By definition, this option plays a greater role in the *solar focus* scenario due to the large share of self-consumption assumed for PV:

- In 2030, the difference in the installed battery storage between the *solar focus* scenario and the *energy transition reference* scenario amounts to approx. 6.4 GW.

- In 2035, this difference increases to 13.6 GW.

- In 2040, it increases to approx. 21 GW.

- In 2050, it increases to approx. 48.0 GW.

Using annuity-based investment costs and including operating costs, the cost difference for short-term storage capacity between the electricity systems of the *solar focus* and the *energy transition reference* scenarios amounts to approx. € 680 million. This corresponds to less than 1% of the total system costs.

The third flexibility option is long-term electricity storage, i.e. the production of hydrogen or other chemical energy sources. With a view to the seasonal characteristics of solar and wind power generation, there is a slightly higher demand in the *energy transition reference* scenario due to the greater storage demand from windy to consistently low-wind seasons. This difference, however, remains small; in 2040 it can reach a maximum of approx. 1.1 GW. Assuming annuity-based investment costs and including operating costs, this corresponds to a difference in the system costs of the scenarios amounting to approx. € 85 million per year or approx. 0.1% of the total system costs.

Finally, a huge expansion of electricity generation based on renewable energies necessitates the expansion and redesign of grid infrastructures. The modelling of grid expansion demand based on the spatial distribution patterns leads to the following results:

- Up to 2025, it can be assumed independently of the scenarios that the redesign of the transmission grids included in the German Grid Development Plan 2025 (hereafter NEP 2025, investment volume of € 30 to 34 billion or annual system costs of € 1.75 to 2 billion) is sufficient to incorporate the electricity production of the renewable power plant fleet.

- For 2035, an additional investment volume of approx. 30% of the NEP is needed in the *energy transition reference* scenario; in the *solar focus* scenario, the investment volume needed for the transmission grid infrastructure is slightly lower, amounting to approx. 23% of the NEP.

- By 2050, the additional grid investment needs amount to approx. 1.3 (*energy transition reference* scenario) and 1.4 times (*solar focus* scenario) the investment volumes specified in the NEP.

- The differences between the two scenarios shift over time from higher investment needs in the *energy transition reference* scenario up to around 2045 to slightly higher investment needs in the *solar focus* scenario for 2045/2050, with the result that the investment needs in the scenarios converge overall.

In terms of the system cost differences, the following cost advantages arise: a maximum of € 170 million (in 2040) for the *solar focus* scenario and of € 150 million (in 2050) for the *energy transition reference* scenario. There are slight deviations over time, which amount to only ±0.2% of the system costs.

The wholesale electricity prices for the two scenarios differ marginally. This results primarily from the development of natural gas and CO_2 prices and in the long term from the increasing generation share of solar and wind power with short-term marginal costs of close to zero.

For the system costs overall, cost advantages arise consistently over time for the *energy transition reference* scenario. These reach maximum levels of only approx. € 1 billion, however, which corresponds to a small system cost advantage of 1.0% to 1.5%.

The following key conclusions can be drawn from the results overall:

- » The transition to an electricity system based entirely on renewable energies is also possible when taking into account the additional electricity demand arising from the decarbonization of the transport and heat sectors if Germany's total greenhouse gas emissions are reduced by 95% compared to 1990.

- » The transition to an electricity system based entirely on renewable energies is possible in various technological designs. There are no significant differences in system costs for the variants examined when all segments of the electricity system are considered (generation, grids, storage, etc.).

- » From an overall perspective, such an expansion of renewable energies is also possible taking into account conservative approaches to land restrictions relating to use, acceptance and nature conservation. After 2045 and in addition to the use of land that is mostly free of restrictions, a small share of land with soft restrictions would need to be used for renewable power generation. This does not apply in the event that the expansion of onshore wind power is slightly lower or when there is a greater focus on solar power, as in the *solar focus* scenario.

- » With a view to land restrictions, the use of onshore wind power and ground-mounted PV systems is decisive to electricity generation from renewable energies. Therefore, the regionalization of electricity production plants based on renewable energies and the investments in long-term infrastructures require greater consideration of topographical particularities and land restrictions. Central requirements for a successful transition to a sustainable energy system, then, are a much more targeted regionalization of the expansion of renewable power generation and the early and proactive addressing of various renewable power generation options and their related land use.

- » Land with restrictions is often also very economically attractive for the development of renewable power generation projects. The corresponding conflicts of land use can only be solved to a very limited extent by general framework conditions and should therefore be addressed at the (land use) planning level. The foundations on which these land use challenges are tackled on the planning level must, however, be considerably improved.

» In all cases, the combined use of land for renewable power generation on the one hand and suitable infrastructure, agricultural or forestry uses on the other hand is a useful approach for limiting land use. This also applies to combined land use for wind and solar power generation.

» With a view to efficient land use, the extensive use of roof-mounted PV systems is a useful overarching strategy. However, the capacities for this are limited; assuming maximum expansion, it can only contribute approx. 23% of the total renewable electricity generation needed. It also involves higher (system) costs, especially if self-consumption is extensively implemented. Furthermore, implementation of roof-mounted PV systems crucially depend on the investment willingness of the respective building or roof owners. In terms of fulfilling the energy transition targets, it involves significant implementation risks.

» The large-scale grid expansion needs differ only slightly overall for the different paths for expanding use of renewable energies in power generation. However, in order to determine the necessary robustness for individual projects, broader development variants for the electricity system should be considered than is the case in Germany's current grid development plans. This applies in particular to the two variants of renewable power generation after 2030 as well as to the variant of a stronger expansion of offshore wind power generation (which was not analyzed in the present study but which remains worth investigating).

» The data basis for strategy development and the associated energy system and infrastructure modelling at regional, national and European levels need to be substantially improved in order to enable realistic and comprehensive analysis.

During the decarbonization of the German electricity system, new challenges will arise and require acceptance. Questions of regionalization, land restrictions and infrastructure expansion will gain new significance and will need to be awarded special and increased consideration in the strategic development of energy and climate policy and in the design of implementation instruments.

1 Introduction

Germany has set long-term targets in the areas of climate and energy policy; the Energy Concept adopted in 2010/2011 (BMWi 2015b) and the Climate Action Plan 2050 published in 2016 (BReg 2016) comprise first steps in developing implementation strategies for climate protection, energy, transport, agriculture, etc. up to mid-century.

Strategies for the complete decarbonization of the energy system have been in high demand since the adoption of the Paris Climate Agreement in 2015 (UNFCCC 2015), yet are still not reflected in Germany's implementation strategies for climate policy. This is crucial if Germany wants to continue its role as a pioneer in climate protection and proactively develop an energy system compatible with the overarching goal of the Paris Agreement, namely to limit global warming to (significantly) less than 2°C, preferably to 1.5°C, compared to pre-industrial levels.

As a result, the short- and medium-term transition of the energy supply towards low- or zero-emission technologies is a central goal in German energy policy, to be achieved primarily by transitioning to renewable energies. This requires robust strategic approaches to design a transformation path that is as effective, broadly accepted, ecologically compatible and cost-efficient as possible.

The transition to a climate-friendly electricity system based on renewable energies forms the central pillar of the necessary processes of change. This prominent role results from, on the one hand, the electricity sector giving rise to the dominant share of greenhouse gas emissions in the total emissions of radiative gases in Germany. On the other hand, the electrification of the transport sector and of substantial shares of heat supply is a crucial lever for bringing about the emission reductions needed in these sectors. As a result, the electricity sector will not only become CO_2-free, it will also have to meet a (significantly) larger electricity demand.

The transition to an electricity system based on renewable energies is a multidimensional challenge. The first challenge is to expand renewable energies at a rapid pace. Secondly, the emission reductions needed for climate protection necessitate the active replacement of fossil electricity generation, particularly CO_2-intensive coal-fired generation. Thirdly, the redesign of the electricity system is coupled with new regional production patterns, for which the necessary (grid) infrastructures must be created.

In the first part of the project "Germany's electric future – Coal phase-out 2035", the different possibilities for a coal phase-out in Germany were analyzed in detail (Öko-Institut & Prognos 2017).

The analyses for the present study, which forms the second part of the project, deal in greater depth with the expansion of renewable energies in electricity generation as well as necessary complementary options such as storage and electricity grids. In view of the manifold possibilities of generating electricity from renewable energies (the different technological approaches of solar and wind power generation as a start, but also in terms of the need to use locations with very different production yields, etc.), it is necessary to examine and evaluate different designs for a renewable electricity system. This is particularly important given the fact that although a renewable electricity system is largely free of greenhouse gas emissions, it will need a far greater land area than the old fossil electricity system. This greater land use applies to wind and solar electricity generation as well as to the necessary grid infrastructures.

As with the capacity of the atmosphere to absorb greenhouse gases, land use for an electricity system based on renewable energies is also subject to clear restrictions, especially in a country like Germany with its high population density and its clear nature conservation and biodiversity targets.

Against this background, it is important and necessary to use an integrated perspective in analyses on the expansion of renewable electricity generation and the necessary grid expansion. This necessitates analyses which, in terms of their spatial differentiation, extend beyond the consideration of nationally aggregated developments on which most model-based analyses on the transition of the electricity system are based.
The second part of the "Germany's electric future" project aims primarily to determine the flexibilities for the expansion of electricity generation based on renewable energies in Germany. The study takes into account potential technical and spatial restrictions and analyzes in greater detail the interactions between different expansion strategies, the need for complementary options (most notably, storage) and for infrastructure, land use and availability as well as costs of the electricity system and its segments. In order to make these complex issues manageable and meaningfully condense them, the various analyses were carried out for two scenarios which could form the design of Germany's future electricity system. The analyses focused on onshore wind power as well as electricity generation from roof-mounted or ground-mounted solar power plants (photovoltaics – PV). A third important option for renewable electricity

generation, offshore wind energy, was not further pursued within the scope of the present study; it will be analysed in greater depth in a future report.

In order to ensure the consistency of the analyses presented here with those made during the project's first phase, a largely identical set of framework assumptions for the energy and CO_2 market environment, the demand sectors and the reduction of the remaining fossil-fired power generation was used in both studies.

2 Methodological approach

In order to be able to develop and analyze two different designs of the future renewable power system, which have different focuses, the following steps were carried out:

1. In order to classify the analyses, various facets of the historical development of the electricity sector were updated for the period from 1990 to 2017 **(chapter 3)**.

2. In a second step, the results from the first phase were consolidated, processed and (with regard to their spatial aspects) further differentiated in view of the development of the fossil power plant fleet **(chapter 4.1)**.

3. As issues concerning electricity grid development feature prominently in the analyses conducted in this study, assumptions relating to the German transmission grid **(chapter 4.5)** were – in addition to the assumptions regarding the market environment, electricity demand and developments in the other European countries **(chapters 4.2 to 4.4)** – documented in greater detail.

4. In a fourth step, the scope of analysis is widened to include two alternative expansion paths for electricity generation plants based on renewable energies **(chapter 5)**. Two representative scenarios for the expansion of renewable electricity generation in Germany were then specified in more detail. These are based, on the one hand, on the currently prevalent projections for expansion (*energy transition reference* scenario) and, on the other hand, on a stronger expansion of solar electricity generation with a focus on self-consumption and a weaker expansion of electricity production from onshore wind power plants (*solar focus* scenario).

5. As a basis for the following electricity sector modelling, the regionalization of area potentials for wind and solar energy generation as well as its use were calculated (with regard to installed capacities and feed-in time series). Land use restrictions and nature conservation interests were also considered and classified. These detailed analyses on regionalization were conducted for the 402 districts in Germany **(chapter 6)**.

6. Building on the above-mentioned steps, a comprehensive quantitative analysis of the two scenarios (*energy transition reference* and *solar focus*) was then carried out using Öko-Institut's electricity market model, in which grid infrastructures can also be considered (Power-Flex-Grid-EU) **(chapter 7)**:

» In a first step, regionalized input data was used to examine the specific situation that would arise if PV systems with battery storage were installed and optimized to a significant extent primarily to meet self-consumption needs **(chapter 7.2)**.

» Using the electricity market model, the electricity system is modelled to calculate the remaining electricity generation, storage use, costs and emissions. With regard to system boundaries, the model ensures compatibility with emission structures and levels of German greenhouse gas inventories and projection reports and thus with the quantity structures of the German emission reduction targets. The modelling takes into account the effects of the ENTSO-E region **(chapter 7.3)**.

» Lastly, a (simplified) load flow simulation is conducted, based on which the expansion needs relating to the German extra-high voltage grid can be estimated **(chapter 7.4)**.

Based on this integrated modelling approach, the following indicators are calculated using the electricity market modelling and discussed:

» the supply, demand and storage capacities needed for electricity;

» the regional structures of electricity generation and cross-border electricity flows;

» the annual CO_2 emissions;

» the respective cumulative CO_2 emissions for the period of 2015 to 2050;

» the utilization of the electricity grid and the resulting grid expansion needs.

7. Based on the data obtained in the sixth step, the economic aspects of the two scenarios are examined in more detail. This applies, firstly, to the effects on wholesale electricity prices. In a further analysis, the system cost differences between the two scenarios are analyzed in greater depth, with a special focus on investment costs **(chapter 7.5)**.

8. In a final step, the results of the different analyses are classified and central conclusions are drawn **(chapter 8)**.

This methodology enables a comprehensive classification and evaluation of expansion paths for electricity generation based on renewable energies. This is compatible with the phase-out path for German coal-fired power generation determined in the first phase of the project and with a climate policy oriented towards a fair distribution of efforts to fulfil the targets of the Paris Agreement.

3 Development of the German electricity sector since 1990

The German power plant fleet has undergone substantial changes over the past 27 years, especially since the turn of the millennium. These changes are mainly attributable to the huge growth of electricity generation based on renewable energies, in particular wind and solar power. Far less pronounced changes can be observed for conventional electricity generation beyond the gradual shutdown of nuclear power plants. There has also been only a slight decrease in dispatchable power plant capacities.[2]

Figure 3-1 shows the development of the net electricity generation capacities in Germany since 1990.[3]

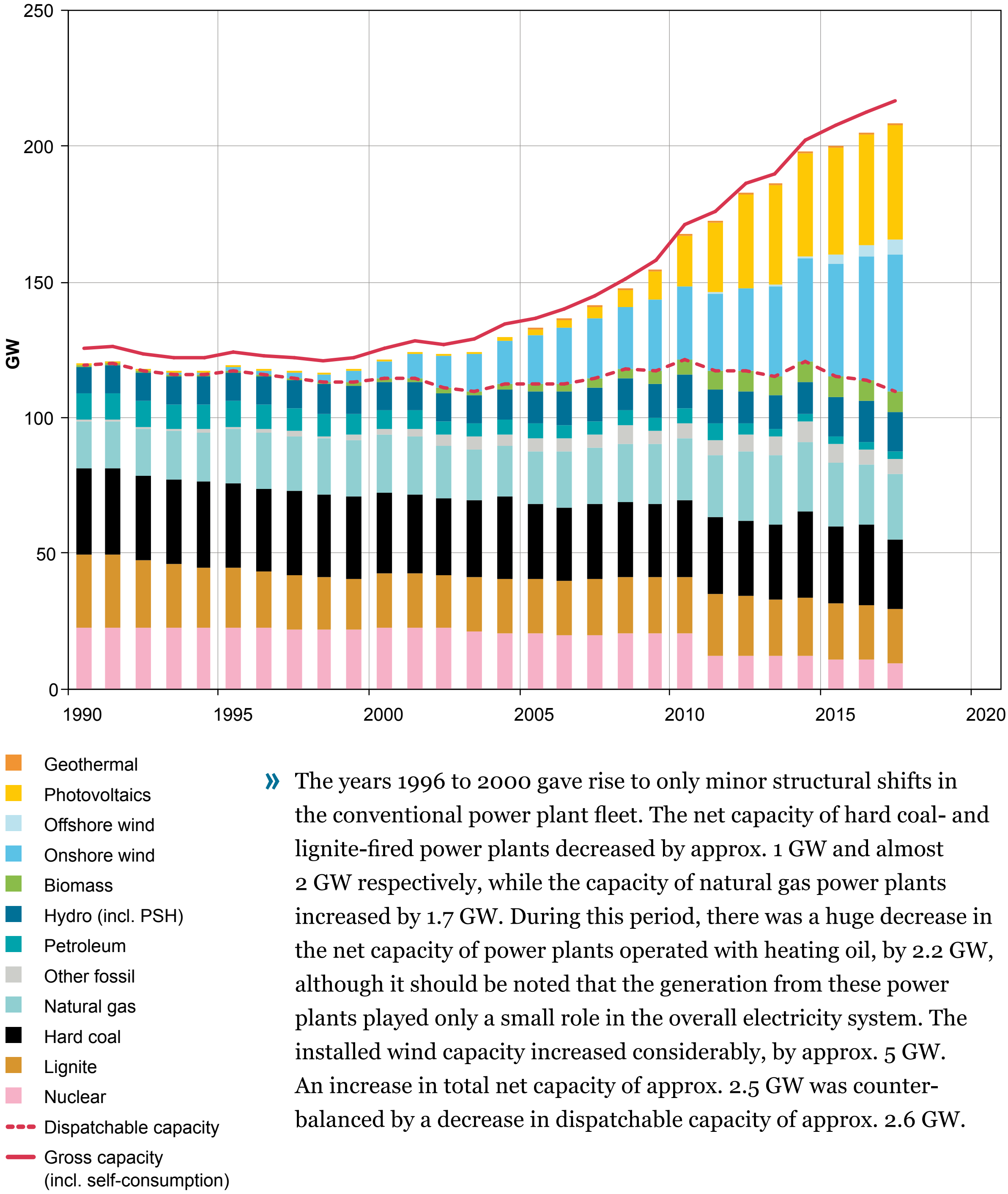
» The years from 1990 to 1995 were shaped by the special circumstances surrounding the reunification of Germany: nuclear power plants in the new federal states (with a capacity in commercial operation of approx. 1.8 GW) were completely shut down in the course of 1990 and the capacities of the East German lignite power plants in particular (mostly industrial power plants) were substantially reduced. Across Germany, the total net capacity of the remaining lignite power plants decreased by approx. 5.3 GW, while the net capacity of natural gas-fired plants rose by 2.5 GW. Overall, total capacity decreased from approx. 120 GW to approx. 118 GW. By this time the installed wind power capacity had already grown significantly to approx. 1.1 GW, such that the total capacity of dispatchable power plants (i.e. excluding wind and solar power plants) decreased from 120 GW to approx. 117 GW.

2 Dispatchable power plant capacities are those capacities whose generation is not dependent on the variable supply from wind and solar energy but rather whose generation (dispatch) is largely determined by the operators. These power plants play an important role in security of supply by facilitating an electricity supply that is demand-responsive at all times.

3 In the following, net power plant capacities are discussed. This data covers the power plant capacity without the capacity needed for self-consumption, i.e. it is the capacity available for grid feed-in or consumption. The reference to net power plant capacity is primarily made to ensure the consistency of historical developments with the modelling of future developments, which is conducted on the basis of net capacities. For the longer historical developments shown here, however, official statistics are only available for gross electricity generation capacities, which include the generation capacities needed for self-consumption. The long series shown for the net electricity generation capacity are based, firstly, on older statistics from the German Federal Ministry for Economic Affairs and Energy (BMWi, so-called IIIB2 statistics) in which net maximum capacities were reported up to 2000, various statistical documents on the situation in the GDR in 1990, the power plant lists of the German Federal Network Agency (BNetzA) from 2015 onwards and our own estimations and adjustment calculations based on the official statistics of BMWi and the Federal Statistical Office (StBA).

Figure 3-1: **Net electricity generation capacities in Germany, 1990–2017**

Source: Federal Ministry for Economic Affairs and Energy (BMWi), Federal Network Agency (BNetzA), calculated by Öko-Institut



» The years 1996 to 2000 gave rise to only minor structural shifts in the conventional power plant fleet. The net capacity of hard coal- and lignite-fired power plants decreased by approx. 1 GW and almost 2 GW respectively, while the capacity of natural gas power plants increased by 1.7 GW. During this period, there was a huge decrease in the net capacity of power plants operated with heating oil, by 2.2 GW, although it should be noted that the generation from these power plants played only a small role in the overall electricity system. The installed wind capacity increased considerably, by approx. 5 GW. An increase in total net capacity of approx. 2.5 GW was counter-balanced by a decrease in dispatchable capacity of approx. 2.6 GW.

» The period of 2001 to 2005 was initially marked by the first shutdowns of nuclear power plants, with net capacity decreasing by approx. 2.1 GW.[4] In the overall balance only marginal changes occurred for lignite power plant capacities, while the net capacities of hard coal-, natural gas- and oil-fired power plants decreased substantially by 1.6, 1.9 and 2.0 GW respectively. Pumped storage capacity, on the other hand, rose by approx. 1.3 GW. The most significant changes involved renewable energies: the generation capacity of wind power plants increased by approx. 9.5 GW, while the capacities of PV and biomass power plants rose substantially, by 1.9 GW and 1.0 GW respectively. Overall, the net capacity of the German power plant fleet increased by 9 GW, while that of dispatchable power plants decreased by approx. 2.3 GW.

» For conventional power plants, the period of 2006 to 2010 saw smaller increases in lignite and coal-fired power plants (approx. 0.7 GW each) as well as a net increase of approx. 3.0 GW in natural gas-fired power plants. However, the growth in wind power (8.6 GW), and especially in solar power (almost 16 GW) and biomass (3.5 GW) clearly dominated changes in the German power plant fleet. The total installed net generation capacity increased by 34 GW. For the first time since 1990, the net capacity of the dispatchable power plants increased substantially again, by approx. 9.4 GW.

» From 2010 to 2017, the changes in the German power plant fleet were shaped, firstly, by the shutdown of almost 11 GW of nuclear power plant capacity. The net capacity of hard coal-fired power plants decreased by 2.7 GW overall, that of the remaining oil-fired power plants by 3 GW and that of lignite power plants by approx. 0.9 GW. The net capacities of natural gas power plants (approx. 1.5 GW) and pumped storage power plants (approx. 2 GW) increased moderately in the balance of power plant start-ups and shutdowns. The capacity of onshore wind power plants increased again, by 23.6 GW. Overall 5.3 GW of offshore wind power capacity was installed. For renewable energies the capacity of PV systems again increased dramatically (24.4 GW), while biomass power plant capacities increased very moderately by approx. 1.5 GW. Overall, the net power plant capacity increased by more than 41 GW, while that of dispatchable power plants decreased by approx. 12 GW.

4 It should be noted that this figure also includes the official shutdown of the Mülheim-Kärlich nuclear power plant (with a net capacity of 1,219 MW) in 2001. This power plant was taken off the grid in September 1988 for legal reasons, but was officially considered operational until 2001 and was listed as such in the official statistics. Unlike the Stade and Obrigheim nuclear power plants, which were decommissioned in 2003 and 2005 respectively, the Mülheim Kärlich nuclear power plant has not contributed to electricity generation since 1989.

The most significant changes to conventional power plants have thus taken place since 2000, i.e. outside the exceptional adjustment process that followed German reunification, which brought about a decrease in the capacities of nuclear energy (by 12.9 GW), oil-fired power plants (by 4.6 GW) and hard coal-fired plants (by 4.7 GW) and an increase in the capacities of natural gas (by 2.9 GW) and pumped storage (by 3.3 GW). For all other fossil-fired power plants, the changes over this period were marginal. In contrast, the capacities of onshore wind power increased by approx. 44 GW, of offshore wind power by 5.4 GW, solar power by 42.3 GW and biomass power plants by 6.1 GW. Overall the total net capacity of power plants increased by more than 87 GW, while the net dispatchable capacities decreased during this period by 4.8 GW.

Hard coal- and lignite-fired power plants currently account for approx. 41% of the dispatchable capacity, natural gas power plants for 22%, hydroelectric power plants (including pumped storage) for 13.5%, nuclear power plants for 9% and biomass power plants for 7%.

Over the past 27 years the net electricity generation[5] of the German power plant fleet (Figure 3-2) has developed in line with capacity development, but has also been strongly shaped by changes in the market environment:

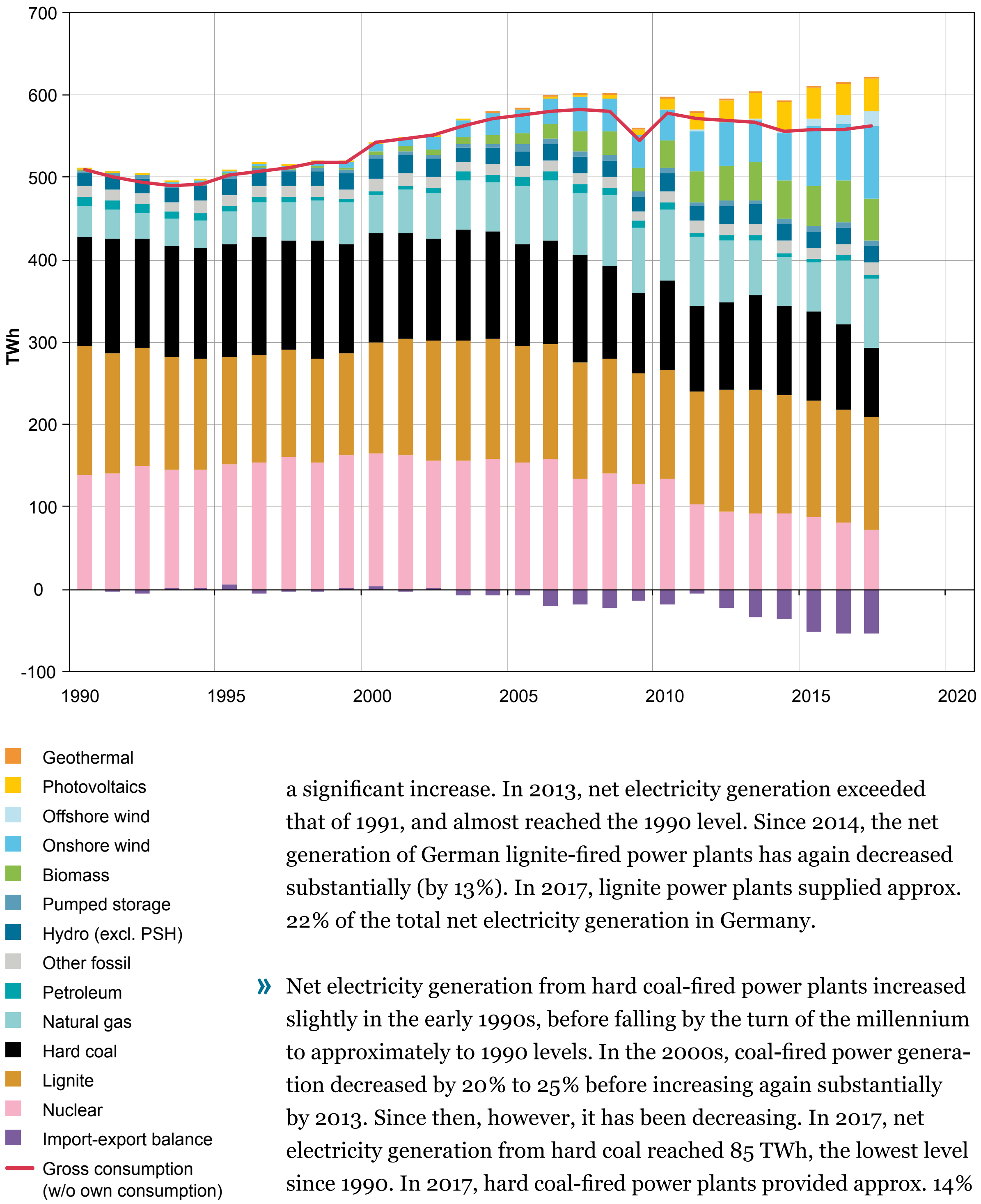
» Net electricity generation from nuclear energy in Germany reached its historic peak in 2001 at approx. 162 TWh (also when electricity generation from nuclear power plants in East and West Germany before reunification are considered) and has been decreasing in the course of the nuclear phase-out. In 2017, nuclear energy contributed approx. 12% of Germany's total net electricity generation.

» The net electricity generation of lignite-fired power plants shows different, i.e. decreasing and increasing trends with a comparatively low overall variance. In the first half of the 1990s it decreased (by 25 TWh or 16%) and then increased up to the turn of the millennium (by 5 TWh). Up to 2007 its generation levels remained relatively stable. They then decreased slightly by approx. 10 TWh; from 2010 to 2013 there was

5 The net electricity generation, i.e. the total (gross) electricity generation of the respective power plants minus own consumption, is presented in the following and in the modelling. This enables better comparability with the results of the modelling of future developments (for methodological reasons, electricity market modelling is always based on net electricity generation). Net electricity generation is only partially differentiated by fuel in the official energy statistics (for the power plants of the general electricity supply). The net electricity generation data by fuel used in this study was reviewed by Öko-Institut, based on all available data sources, as a consistent quantity structure.

Figure 3-2: **Net electricity generation and gross electricity consumption in Germany, 1990–2017**

Source: Working Group on Energy Balances (AGEB), German Federal Ministry for Economic Affairs and Energy (BMWi), German Association of Energy and Water Industries (BDEW), calculations by Öko-Institut



a significant increase. In 2013, net electricity generation exceeded that of 1991, and almost reached the 1990 level. Since 2014, the net generation of German lignite-fired power plants has again decreased substantially (by 13%). In 2017, lignite power plants supplied approx. 22% of the total net electricity generation in Germany.

» Net electricity generation from hard coal-fired power plants increased slightly in the early 1990s, before falling by the turn of the millennium to approximately to 1990 levels. In the 2000s, coal-fired power generation decreased by 20% to 25% before increasing again substantially by 2013. Since then, however, it has been decreasing. In 2017, net electricity generation from hard coal reached 85 TWh, the lowest level since 1990. In 2017, hard coal-fired power plants provided approx. 14% of total net electricity generation in Germany.

» Net electricity generation from natural gas-fired power plants increased strongly and comparatively steadily from the early 1990s onwards. In 2010 it reached an initial peak at around 2.3 times the 1990 level. However, due to unfavourable market conditions (high price differences between natural gas and coal, low CO_2 prices), natural gas-based electricity generation once again decreased by almost a third by 2014/2015 and was limited primarily to combined heat and power plants designated for public electricity supply, to own consumption of industry and to other decentralized uses. However, within the scope of changed market conditions (most notably low prices for natural gas and increased emission allowance prices), electricity production from natural gas, including in modern condensing power plants, substantially increased again in 2016 and 2017. The previous peak level of 2010 (approx. 87 TWh) was nearly reached again in 2017 (84 TWh). In 2017, the share of natural gas generation in total net electricity generation was, at 13.5%, for the first time almost equal to that of hard coal.

» Net electricity generation from renewable energies has risen dramatically, particularly since the turn of the millennium. With a total generation of 151 TWh in 2013, renewable energies exceeded the level of lignite generation (2013: 149 TWh) for the first time; in 2014 it drew level, at 162 TWh, with the peak of electricity generation from nuclear energy in Germany (2001: 162 TWh). By 2017, net electricity generation based on renewable energies had risen to 218 TWh, almost reaching the net generation from lignite and hard coal-fired power plants combined. Renewable electricity generation is currently dominated by onshore wind (approx. 14% of total net electricity generation). With the exception of lignite, onshore wind power generation exceeds all conventional generation options. It is followed by biomass (8%) and PV (approx. 6.5%). Offshore wind power currently represents around 3% of total net electricity generation and is substantially increasing. Lastly, geothermal energy continues to play a smaller role, accounting for 0.02% of total net electricity generation in Germany.

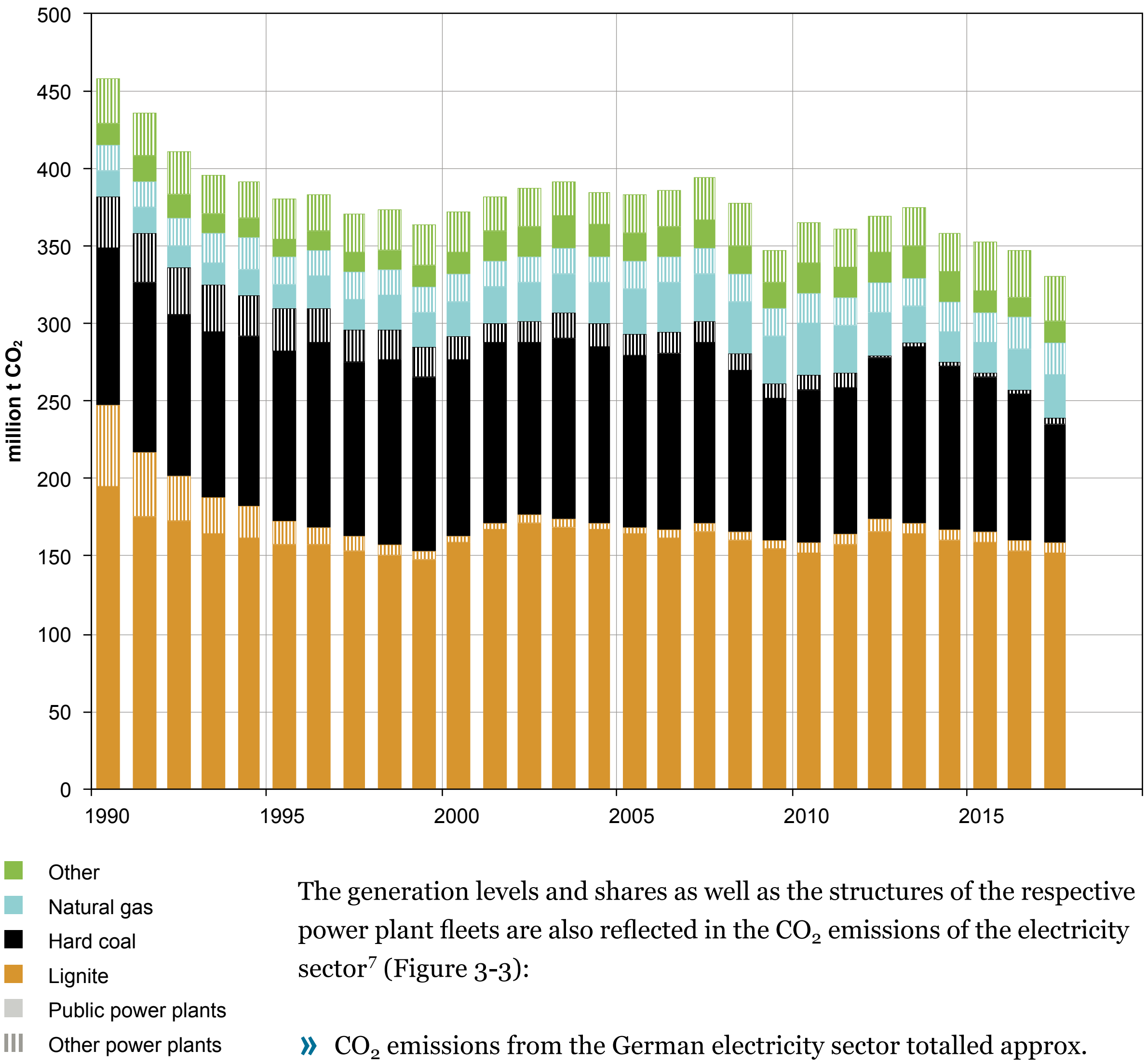
» Finally, it should be noted that net electricity exports from Germany have hugely increased since the turn of the millennium. Prior to 2000 its electricity imports and exports were generally balanced, with the exception of a very few years. Net electricity exports have risen significantly from 2003 onwards and have reached new peaks annually since 2012. Given the contribution margins and the marginal cost structure, its net electricity exports now mainly come from generation plants with relatively low fuel costs and high CO_2 emissions, i.e. primarily coal-fired plants. Overall, almost 9% of Germany's total net electricity generation is currently exported. It should also be noted that the change in the electricity balance is the result of decreasing electricity imports and a huge growth in electricity exports.

In contrast to the very substantial structural changes occurring in some areas of its electricity generation mix, the development of gross electricity consumption in Germany (excluding own consumption[6]) can be clearly divided into three phases. From 1990 to 2007, gross electricity consumption increased from 509 TWh to 583 TWh (by approx. 14%) before sharply decreasing in 2009 in the wake of the financial and economic crisis. Following the economic recovery in 2010, gross electricity consumption continued to decrease slightly until 2014 at which point it began rising again slightly, reaching approx. 564 TWh in 2017.

6 The own consumption of power plants was not included in the values for supply and demand in order to provide an appropriate basis for analysing net power plant capacity and net electricity generation.

Figure 3-3: **CO_2 emissions from electricity generation in Germany, 1990–2017**

Source: German Federal Environment Agency (UBA), Federal Statistical Office (Destatis), German Association of Energy and Water Industries (BDEW), calculations by Öko-Institut



The generation levels and shares as well as the structures of the respective power plant fleets are also reflected in the CO_2 emissions of the electricity sector[7] (Figure 3-3):

» CO_2 emissions from the German electricity sector totalled approx. 330 million t CO_2 in 2017, approx. 27.5% and 13% below the 1990 and 1995 values respectively (the values for 1995 are used as a robust reference to account for the effects of Germany's reunification). Emissions from the electricity sector made up 35.5% of Germany's

7 In this study, the CO_2 emissions from the electricity sector are defined according to the "power plant concept". All CO_2 emissions released into the atmosphere by electricity generation plants are hereby attributed to the electricity sector, even if these plants also generate by-products such as heat. There is no quantitative allocation of emissions to the respective products (as would occur when using the "generation concept") since this would make little sense for the issues handled in the present study.

total greenhouse gas emissions (considering non-CO_2 gases and emissions from fuel quantities tanked in Germany for international transport) in 2017. This remains above the levels of 1995 (33.5%) and just below those of 1990 (36%).

- Lignite-fired power plants currently account for the largest share of electricity sector emissions, at 48%. It is worth noting here that emissions from lignite-fired power plants in 2017 came almost entirely from public utilities (approx. 46%) with only a very small share (approx. 2%) coming from other power plants.[8] This situation differs markedly from the situation in 1990 (approx. 42 and 11 percentage points with a total share of 54%). From 1990 to 2017 there was a 21% decrease in emissions from public lignite-fired power plants and an 87.5% decrease in emissions from other lignite power plants. In total, CO_2 emissions from lignite-fired power plants decreased by 35% between 1990 and 2017; it should be noted, however, that the development between 1990 and 1995 is predominantly attributable to reunification-related adjustment processes in the new federal states, which primarily involved very inefficient (lignite-fired) combined heat and power power plants of industry (i.e. outside of public supply). The emission trends for lignite have been uneven. Since 2012, CO_2 emissions from German lignite-fired power plants have decreased slightly (by 16 million t CO_2).

- Hard coal-fired power generation accounts for the second largest share of emissions from the electricity sector; it currently accounts for approx. 24.5%. Here too, the share of hard coal-fired power plants in total public power supply is currently very high, at approx. 23 percentage points, with other power plants accounting for just under 1 percentage point. Again, the situation in 1990 was structurally very different, with the share from public utilities amounting to approx. 22% and that of other power plants to approx. 7%. Emissions from all coal-fired power generation decreased by approx. 39.5% between 1990

8 In the context of emission inventories, other power plants include refinery plants, power plants of the remaining conversion sector and the remaining power plants of the manufacturing industry (industrial power plants). Public utilities are reported in the national greenhouse gas inventories under the energy industry category (Category 1A1), together with refinery power plants, power plants of the remaining conversion sector and the heat-only generators of district heating supply, refineries and the remainder of the conversion sector. Emissions from industrial power plants in the remaining manufacturing sectors do not fall under the category of energy industry; instead, they are classified with the heat-only generators of the remaining manufacturing industry under the category of manufacturing and construction (Category 1A2).

and 2017; the 24% decrease from public utilities was much smaller than the decrease in the various industrial sectors (87%). There have also been inconsistent trends for hard coal-fired power plants over the past 27 years; however, the emissions have decreased sharply since 2013 (by 35.5 million t CO_2).

- Natural gas electricity generation accounts for approx. 15% of the current CO_2 emissions from the electricity sector. Of this, 8% originate from public utilities and approx. 6% from other power plants. With the overall share of natural gas electricity generation having increased significantly since 1990, the ratio of public to industrial natural gas-fired electricity generation has changed only slightly (approx. 4 percentage points each in 1990). In contrast to coal-fired power generation, emissions from natural gas-based power generation have risen significantly since 1990, by approx. 71% for public utilities and approx. 23% for other natural gas-based power generation. In total, CO_2 emissions from natural gas have increased by 47% since 1990. The current emission levels were reached in 2010 and have fluctuated strongly in the years in between.

- Emissions from power plants fired by other fossil fuels (particularly by-products of the steel industry, petroleum products and non-organic waste) have reached similar levels. Their share in overall emissions reached 13% in 2017, 4% of which came from public utilities and 9% from other power plants. For comparison, the relative share of emissions for this category in 1990 was approx. 10%, with approximately one third from public utilities and two thirds from other power plants. Overall the emissions changed little from 1990 to 2017, amounting to 2% above 1990 levels in 2017. The CO_2 emissions from public utilities decreased by 9% during this time, while emissions from industrial power plants increased by approx. 1%.

With a view to the emission reduction targets for the German electricity sector, the following conclusions can be drawn from the stated emission levels (Öko-Institut 2018):

- To achieve the 40% emission reduction target (for 2020), total electricity sector emissions should not exceed 250 million tonnes of CO_2, assuming that other sectors were to contribute 50 million tonnes of CO_2 to emission reduction compared to current levels. If other sectors do not make an additional contribution to reducing emissions, i.e. if greenhouse gas emissions can only be stabilized, CO_2 emissions from the electricity sector should not exceed 200 million tonnes.

- The sectoral emission reduction targets of Germany's Climate Action Plan 2050 (BMUB 2016) allow a maximum emission of 180 million tonnes of CO_2 for the electricity sector in 2030.

Strategies for substantial and long-term emission reductions in the electricity sector must therefore address the approx. 70% share of emissions from coal-fired power plants as a high priority. At the same time, the growth dynamics of power generation from renewable energies in the past five years (which averaged an increase of approx. 15 TWh) must be continued in the coming decades at the least, if not (slightly) increased. Given the expected shutdown of an increasing number of older renewable power plants in the coming years, an annual net increase in electricity generation of 15 TWh or more necessitates a substantial expansion of power plants based on renewable energies, especially wind and solar power. The regional aspects and implications of such an expansion will play an increasingly important role.

4 Framework assumptions for modelling

4.1 Conventional power plant fleet in Germany

The compatibility of the transformation processes of the German electricity sector with the overall goals of the Paris Agreement is a decisive boundary of action in the modelling. In the diverse analyses in the field of climate modelling, emissions budget modelling has proven to be a pragmatic approach for linking global warming and GHG emissions development to derive courses of action. These analyses mainly focus on the cumulative emissions of the most important greenhouse gas, CO_2, over certain periods of time, thus forming a robust indicator for the various emission developments.[9]

In the first phase of the present project, the concept of a fair share of the global CO_2 emissions budget for Germany and a detailed definition of the emissions budget for the German electricity sector were developed (Öko-Institut & Prognos 2017):

- The cumulative global CO_2 emissions from 2015 onwards should not exceed a value of 890 billion t CO_2 in order to avoid, with sufficient probability, a change in the global climate and its consequences for ecosystems and human societies that would no longer be acceptable.

- As the German population represented about 1.1% of the global population in 2015, a per capita distribution would result in a German emissions budget of about 9.9 billion tonnes of CO_2, which would satisfy the criterion of fairness.

- In view of the current emission shares, the emissions budget for the German electricity sector from 2015 onwards amounts to 4.0 to 4.2 billion t CO_2.

9 In order to ensure consistency with the IPCC data on which the following is based, only the CO_2 emissions are considered in this study and other greenhouse gas emissions are excluded. This constitutes a useful and robust approach given the clear dominance of CO_2 emissions in Germany's total (energy-related) emissions.

The first phase of the present project, which addresses the phase-out path for coal-fired plants in Germany under the conditions of such an emissions budget, shows that it is only possible to keep within this emissions budget if significant emissions reductions can be implemented quickly and with a hugely accelerated expansion of electricity generation based on renewable energies. The models described below are based on the "transformation scenario" developed in Phase 1 of this project. This includes an integrated assessment of emission reductions (cumulative CO_2 emissions) and the guarantee of a high security of supply (stable shutdown of dispatchable generation capacities). The transformation scenario is based on the following boundaries of action and strategic approaches for fossil power generation:

- Coal-fired generation ends in 2035. Therefore, almost all power plants operated in Germany can continue to operate for a further 20 years with no additional restrictions.[10]

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

- From their 21st operating year, all coal-fired power plants must be subject to an emission-based optimization process. This process must correspond to the British Emission Performance Standards (EPS), which restrict the annual emissions budget of a coal-fired power plant to 3.35 t CO_2/kW.

- Analogously to phase 1 of the present project, 99 GW of dispatchable power plants or appropriate equivalents are made available on the demand or storage side to ensure a high degree of security of supply. This also includes corresponding contributions to electricity capacities made by other countries.[11]

10 The only exception here is Datteln 4 power plant, for which a specific solution must be found, should it be put into operation.

11 The simplified approach for evaluating security of supply, which was developed during the first phase of this project, assumes that approx. 15% of the net capacity of dispatchable power plants is not available for meeting the peak load of 84 GW for different reasons (revisions, various production restrictions, etc.) (Öko-Institut & Prognos 2017).

Figure 4-1: **Dispatchable power plant capacities in the transformation scenario, 2015–2050**

Source: Öko-Institut and Prognos

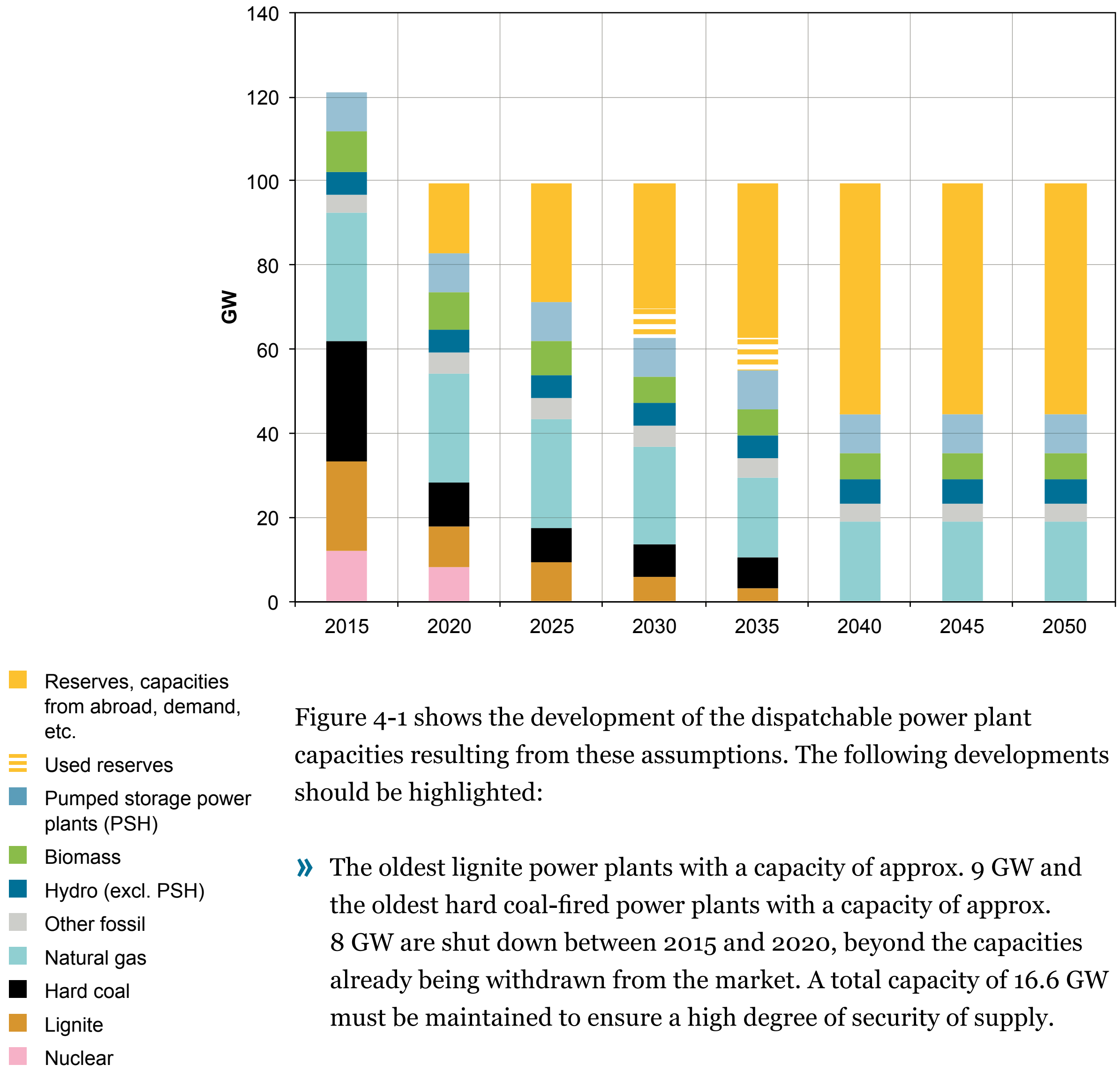


Figure 4-1 shows the development of the dispatchable power plant capacities resulting from these assumptions. The following developments should be highlighted:

- The oldest lignite power plants with a capacity of approx. 9 GW and the oldest hard coal-fired power plants with a capacity of approx. 8 GW are shut down between 2015 and 2020, beyond the capacities already being withdrawn from the market. A total capacity of 16.6 GW must be maintained to ensure a high degree of security of supply.

- Between 2020 and 2025, 2.5 GW of older hard coal-fired power plants are decommissioned without a need to secure further capacity.

- Between 2025 and 2030, 3.5 GW of lignite power plants are decommissioned.

- From 2030 to the end of 2035, all newer lignite power plants with an overall capacity of 5.7 GW and the remaining (newer) hard coal-fired power plants with a capacity of about 7.7 GW are shut down.

- In view of the limited availability of sustainable biomass and the corresponding demand in other sectors, the total capacity of biomass power plants decrease by a third between 2020 and 2030 and then remain at a level of 6 GW.

- The capacity of natural gas-fired power plants, which are used above all to generate significant quantities of electricity, remain roughly constant from 2020 to 2030 and then decrease by about a quarter.

- With the shutdown of considerable nuclear and coal-fired power plant capacities, the demand for flexible power plants or demand-side flexibility increases. These flexibile capacities primarily serve to cover (residual) peak loads rather than simply produce large quantities of electricity. Gas-fired power plants can be used for this purpose, although they compete with other options. Such options include measures to make demand more flexible, capacities from power plants located abroad and, in the longer term, various storage technologies. The contributions to flexibility depend on the following: (1) technological developments (e.g. storage); (2) a robust market design (that ensures sufficient and competitive financing of investments and coordinated operation); and (3) basic political decisions (above all with regard to capacities from abroad). The flexibility options are summarized ("Reserves, capacities from abroad, demand, etc.") as sufficiently robust trends are not yet foreseeable.

4.2 Fuel and CO_2 prices

Assumptions about future fuel and CO_2 prices influence both the use of conventional power plants and their general profitability. At the same time, the future development of these parameters involves high uncertainties.

As the present study builds on the first phase of the overarching project, it makes sense for most assumptions to match those of the first phase. The original assumptions were only adapted if the expectations regarding future developments or other external framework conditions have changed so significantly in the prior two years that it was no longer reasonable to maintain them.

In order to achieve the most robust results possible, the model analyses from the first phase of the project ("Germany's electric future – Coal phase-out 2035") assume that global energy market developments tend to be unfavourable for climate protection and energy policy.

The framework assumptions for the import and export prices of fuel are based again on the oil price projection in the reference scenario of the Annual Energy Outlook 2014 (EIA 2014), which was prepared by the Energy Information Administration (EIA) of the US Department of Energy.

The prices for natural gas, hard coal and heating oil were derived on the basis of projections for crude oil prices. Econometric analyses of the relationship between the respective prices were used, from which relatively robust explanatory patterns were derived for long-term trends. The prices at which these fuels are available, including transport to the power plants, were then derived from these wholesale prices.

To calculate lignite prices, which are not dependent on the developments of the global fuel markets in the final analysis, the short-term marginal costs of lignite production of 1.50 €/MWhth were again used in the calculations.

The CO_2 costs are an important parameter for determining the emission intensity of the remaining fossil power plant fleet and thus for the emission development of the electricity sector. Their influence on power plant dispatch overall decreases, however, with an increasing share of renewable energies in electricity generation. A development that was as realistic as possible was assumed for the costs of emission allowances (European Union Allowances – EUA) in the first phase of the project and again in the present study.

Table 4-1 shows the fuel and CO_2 prices used in the modelling, which are dependent on the different scenario years. The calculations were based on 2010 prices.

Table 4-1: **Development of fuel and CO_2 prices (based on 2010 prices)**

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

		Current	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

4.3 Electricity demand in Germany

An essential input parameter for the modelling is the estimation of future demand. The electricity demand assumed for Germany in the first phase of the project is also used in the present study. It was calculated based on the following:

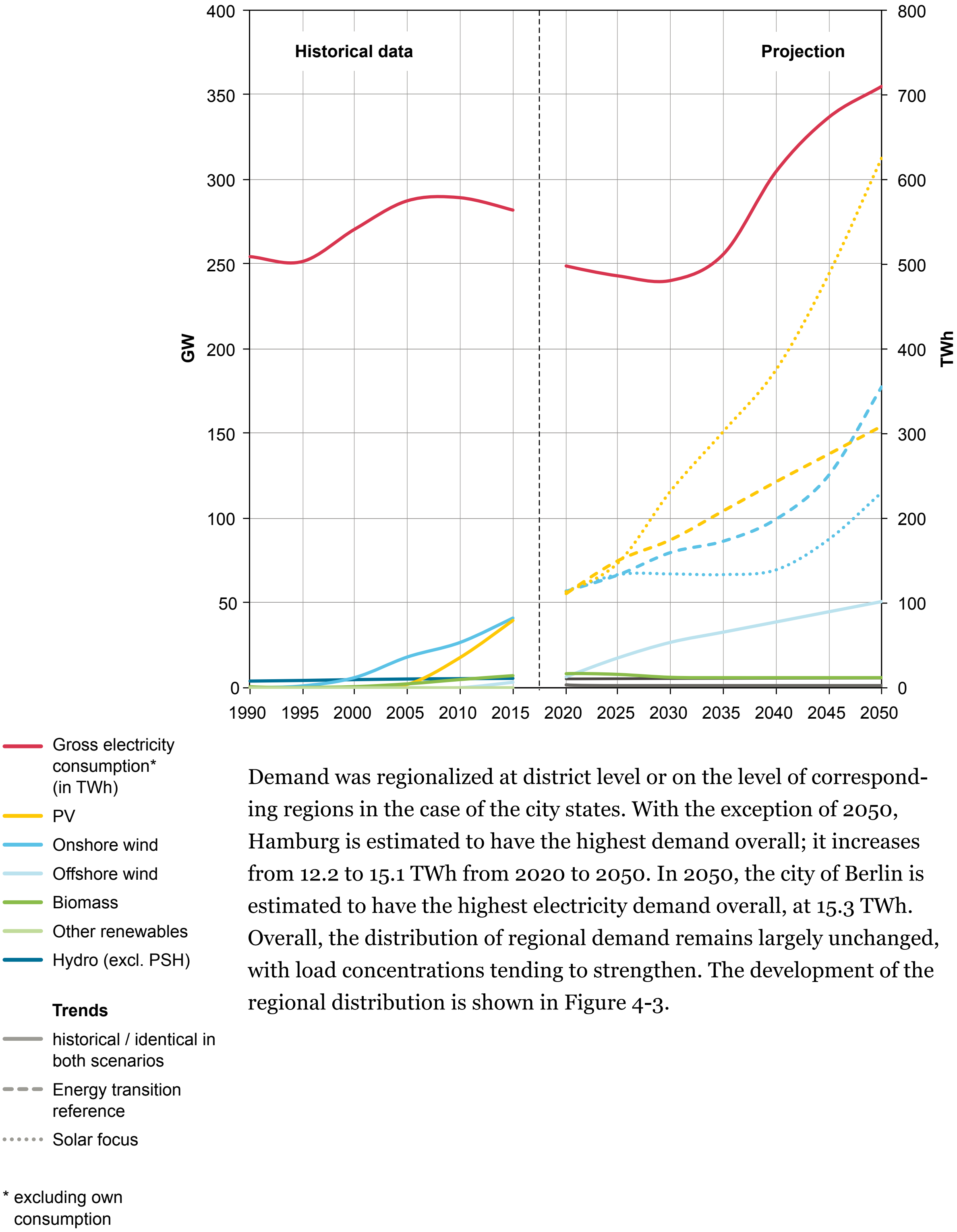
- Analyses of an emission reduction scenario of 95% compared to 1990 levels were used to calculate demand (Öko-Institut & Fraunhofer ISI 2015). The gross electricity demand (excluding own consumption of power plants) is shown in Figure 4-2.

- A major trend is observed in the effectiveness of efficiency measures, which have a decisive impact on the absolute electricity demand. Thus, gross electricity consumption is assumed to be approx. 500 TWh for 2030.

- The development after 2030 is shaped by the increasing demand for new electricity applications (transport, heat, possibly electricity-based synthetic fuels, etc.), such that the historical electricity demand levels are substantially exceeded. For 2050, this results in a gross demand of approx. 700 TWh.

Figure 4-2: **Gross electricity demand and expansion of renewable electricity generation capacities, 1990–2050**

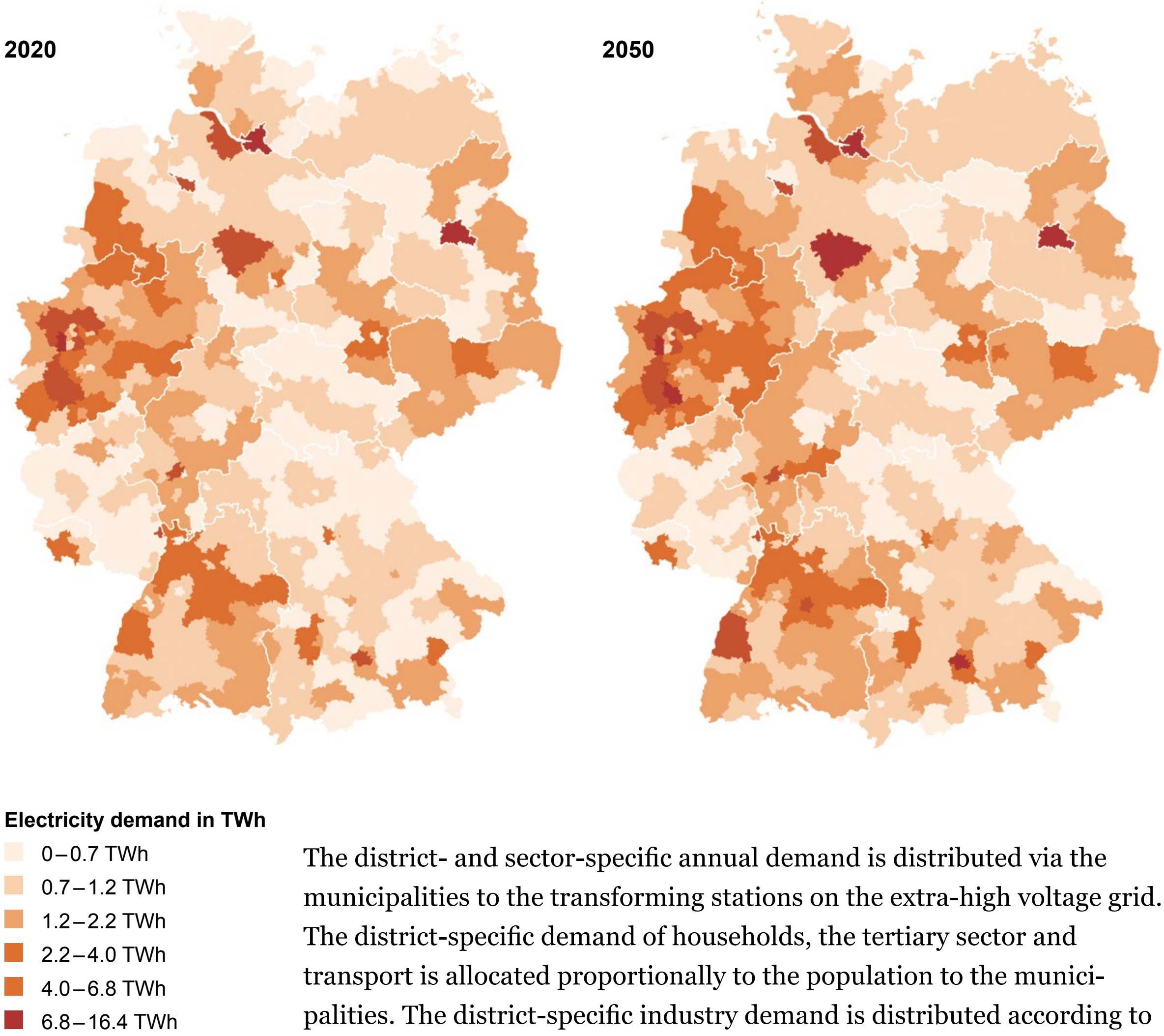
Source: Calculations by Öko-Institut



Demand was regionalized at district level or on the level of corresponding regions in the case of the city states. With the exception of 2050, Hamburg is estimated to have the highest demand overall; it increases from 12.2 to 15.1 TWh from 2020 to 2050. In 2050, the city of Berlin is estimated to have the highest electricity demand overall, at 15.3 TWh. Overall, the distribution of regional demand remains largely unchanged, with load concentrations tending to strengthen. The development of the regional distribution is shown in Figure 4-3.

Figure 4-3: **Annual electricity demand at district level, 2020 and 2050**

Source: Öko-Institut, based on calculations by Prognos



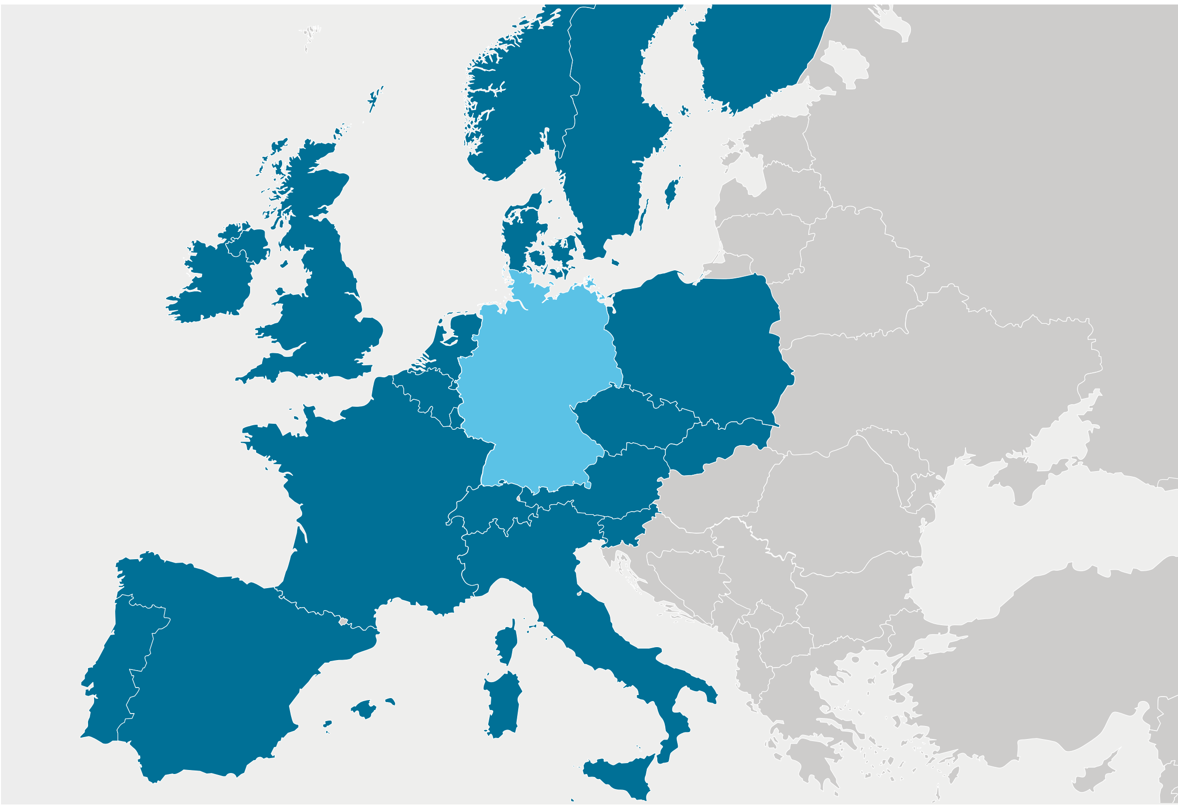
The district- and sector-specific annual demand is distributed via the municipalities to the transforming stations on the extra-high voltage grid. The district-specific demand of households, the tertiary sector and transport is allocated proportionally to the population to the municipalities. The district-specific industry demand is distributed according to the municipality-specific industrial load of electricity-intensive manufacturing industry. The final classification of the municipalities to the transforming stations is carried out using a geometrical method called Voronoy decomposition and also taking into account the regional boundaries of the transmission grid operators.

4.4 Development of power plant fleets outside of Germany

Due to the increasing convergence of the European electricity market, the developments of the German electricity market also fundamentally depend on the framework conditions in Europe. The assumptions regarding the European electricity market from the first phase of the project were retained as far as possible in the present study.[12]

The assumptions regarding the development of electricity demand and the power plant fleet in Europe are thus crucial parameters for the development of the German electricity system. This especially applies to the CO_2 emissions of the German electricity sector and to the integration of an increasing share of variable renewable energies and to ensuring security of supply in Germany.

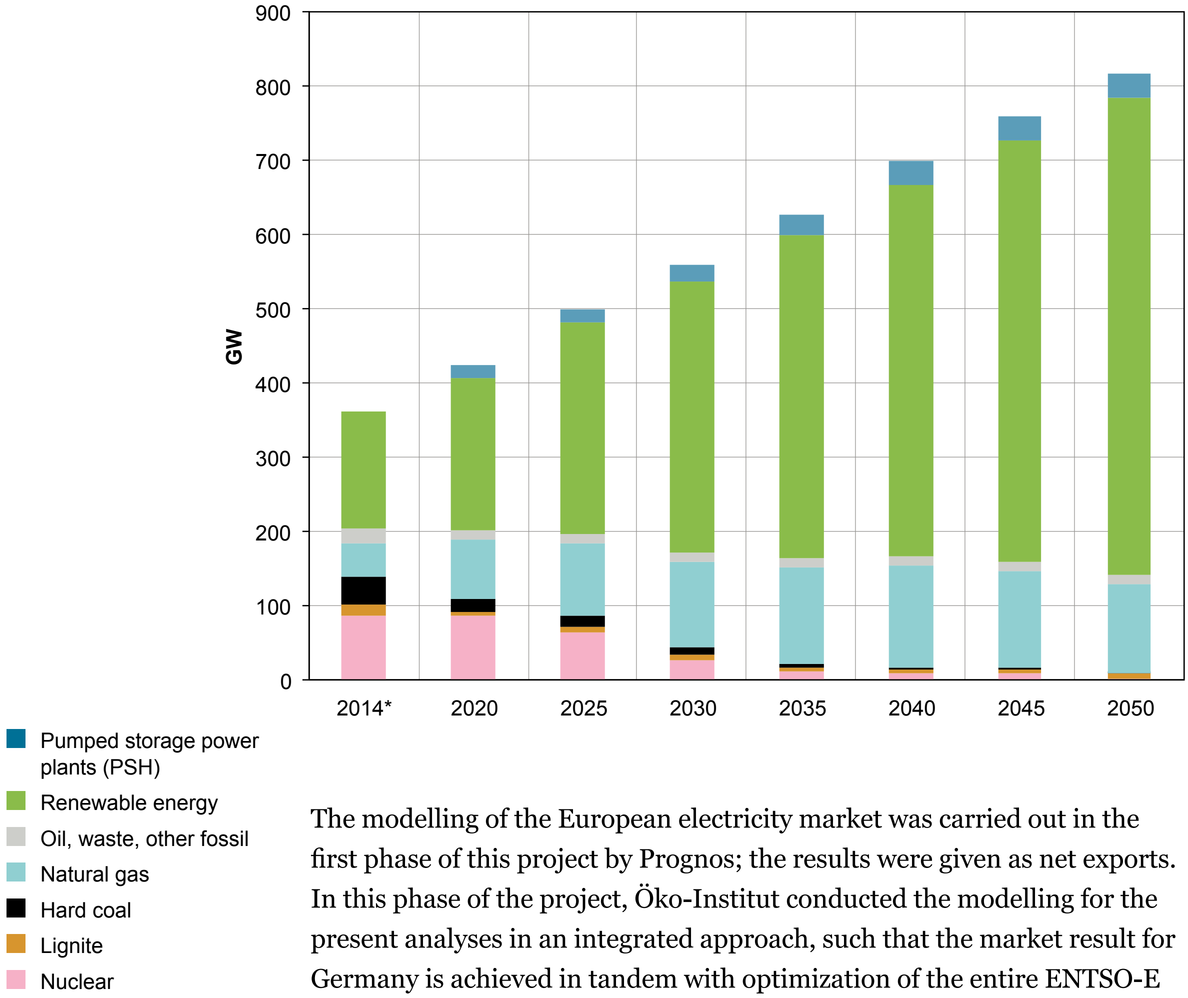
Figure 4-4: **Regional boundaries for modelling the electricity market**
Source: Öko-Institut



12 For a detailed description of the individual assumptions for the different countries, see Öko-Institut & Prognos (2017) and Annex 3.

Figure 4-5: **Expansion of electricity generation capacities of Germany's electricity neighbours, 2020–2050**

Source: Calculations by Öko-Institut and Prognos based on EntsoE (2014)



* PSH capacities not included for 2014, SE/NO incl. peat, DSM data not available

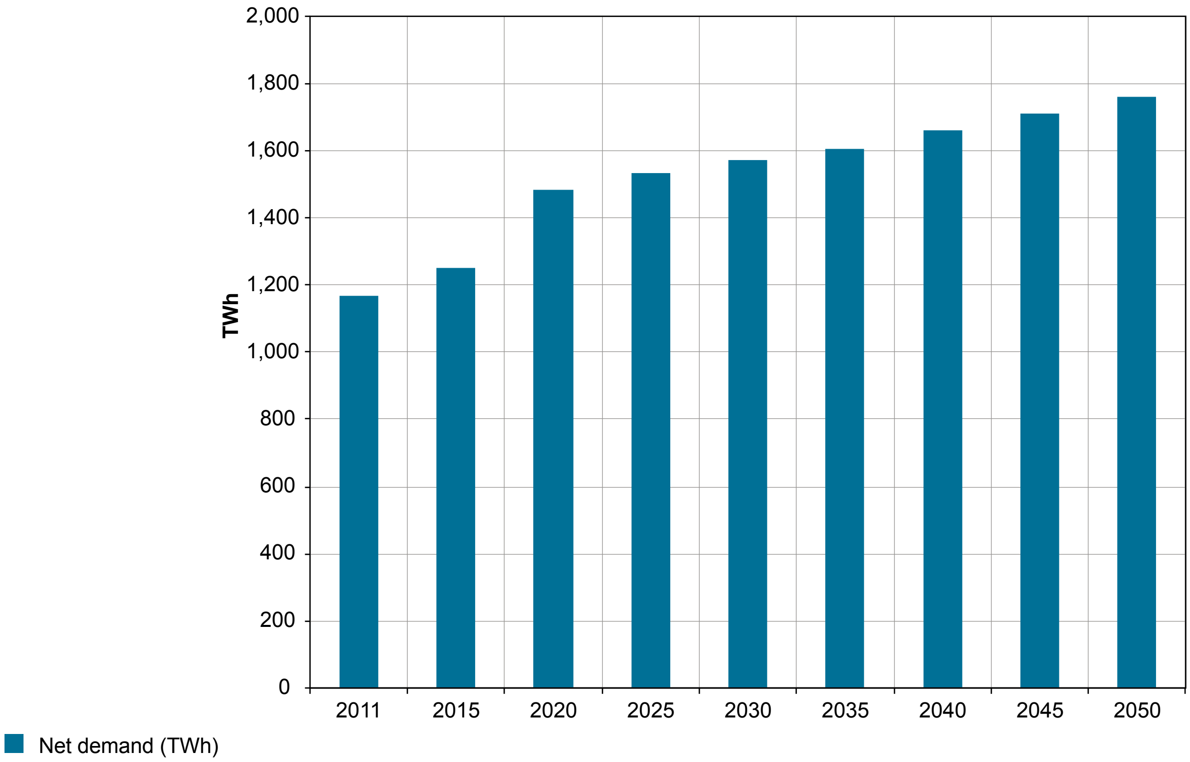
The modelling of the European electricity market was carried out in the first phase of this project by Prognos; the results were given as net exports. In this phase of the project, Öko-Institut conducted the modelling for the present analyses in an integrated approach, such that the market result for Germany is achieved in tandem with optimization of the entire ENTSO-E region (see Figure 4-4).

As in the first phase of this project, the input data and results incorporate the direct European neighbours: Austria, Switzerland, France, Luxembourg, Belgium, the Netherlands, Norway, Denmark, Sweden, Poland and the Czech Republic. These so-called "electricity neighbours" are areas which currently have – or in the case of Norway and Belgium will foreseeably have – direct electricity grid connections to Germany.

Figure 4-5 shows the aggregated development of fuel-specific electricity generation capacities of Germany's electricity neighbours from 2014 to 2050. This overview of its development clearly manifests an orientation towards the European climate protection targets: the developments in

Figure 4-6: **Electricity demand of Germany's electricity neighbours, 2011–2050**

Source: Öko-Institut and Prognos



neighbouring European countries show a very strong increase in electricity generation capacities based on renewable energies.[13]

Figure 4-6 shows the development of the electricity demand of Germany's electricity neighbors from 2014 to 2050 as another fundamental input parameter of the modelling. For the countries considered it is assumed that the electricity demand increases in the future due to a stronger penetration of electricity applications in terms of electric mobility and space heating. In total, the electricity demand in these countries increases by approx. 500 TWh by 2050 compared to 2015.

13 The country-specific quantities for the development of conventional and renewable energies over time can be found in Annex 3.

4.5 Assumptions relating to Germany's transmission grid

The electricity grid was not modelled separately in the first phase of the project. However, since regional aspects of the expanding electricity generation based on renewable energies form the focus of the present analyses, separate modelling of the electricity grid was undertaken. Corresponding assumptions had to be made for this purpose, which have no influence on the market results of the modelling. Rather, they are used to determine the resulting load flows of the individual power lines and to estimate the necessary grid expansion.

The dimensionalities of the electricity grid at the start of the analysis are important for estimating the grid expansion needs. This grid is referred to as the "starting grid". It is assumed that the grid expansion needs identified to date will have been realised in 2020 and are therefore no longer shown.

Within the scope of this project, the target grid defined in the second draft of Germany's Grid Development Plan for Electricity 2025 (50Hertz Transmission GmbH et al. 2016) for Scenario B2 2025 was adopted as the starting grid of this analysis.[14] The following arguments support the use of this approach:

- The accuracy of the load flow simulation results depends decisively on the quality of the grid data set used. Öko-Institut obtained the processed data for the target grid developed for the GI variant of Scenario B2 2025; this data was provided by the Federal Network Agency (BNetzA) in accordance with §12f.[15]

- The NEP 2025 provides a very detailed determination of the grid expansion needs up to 2025. As a starting point for the present analyses it is assumed that it makes sense, independently of the scenarios, to implement the grid expansion needs identified in NEP 2025 by 2050 at the latest. This makes it unproblematic in the estimation of the

14 Due to significant changes in the legal framework conditions during the development of the Grid Development Plan 2025, the process was halted in 2017 after the second draft was submitted to the Federal Network Agency. The grid expansion needs defined therein were thus not confirmed by the Network Agency. It can be assumed that the target grid developed by the transmission system operators has relatively generous dimensions.

15 The more recent grid data set for the NEP 2030 was compiled by Öko-Institut. It is based on the 2025 grid and takes into account the information on grid expansion needs stipulated in the NEP 2017-2030; and is therefore of somewhat lower quality.

additional grid expansion needs that there may be different estimates of the starting grid's dimensions in its early years. Therefore, using this starting grid as a reference is a very robust assumption.

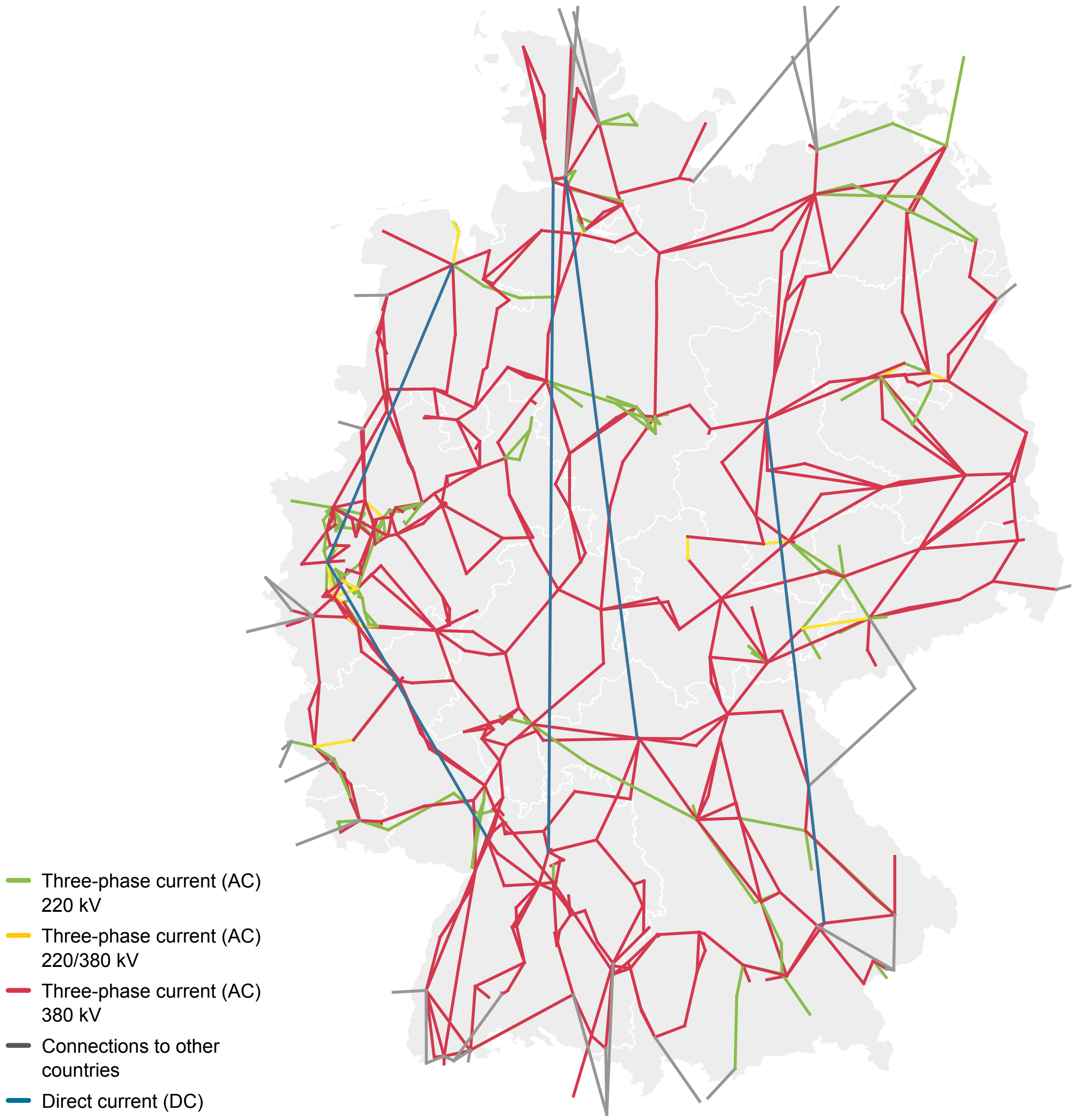
» The estimated grid expansion needs should take the form of investment needs. The results of the NEP 2025 also provide a robust basis for this purpose.

» The aim of this project is in particular to estimate the extent to which the grid expansion needs differ between the scenarios examined, i.e. the extent to which they depend on the technology-specific and regional expansion path of renewable power generation. In 2020 and 2025, the expansion paths of renewable power generation are still close together in both scenarios. Only from 2030 onwards do they significantly diverge. Thus the grid expansion needs should be analyzed from 2030 onwards. Up to this year, it can be assumed that the majority of the grid expansion needs identified in the NEP and confirmed in the Federal Requirement Plan of the German Federal Parliament are achieved.

The grid data set prepared by the Federal Network Agency (BNetzA) for the load flow simulation maps the German 380/220 kV electricity grid in a way that is as detailed as possible in respect of the substations. This mapping consists of approx. 820 power lines between about 560 grid nodes, see chapter 7.4.3. Figure 4-7 shows the NEP B2 2025 target grid used in this model.

Figure 4-7: **Grid topology analogous to Grid Development Plan B 2025 (independent of scenarios)**

Source: Öko-Institut



The second draft of the NEP 2025 identified the following grid expansion needs for Scenario B2 2025 (50Hertz Transmission GmbH et al. 2016):

» investment volume for full cabling of direct current (DC) lines:
€ 34 billion

» construction of new direct current (DC) lines:
3,200 km

» construction of new alternating current (AC) lines:
1,100 km

» expansion measures for existing power lines:
5,800 km

In the context of grid data a further assumption requires the scope of potential grid expansion measures to be defined. For this project it was assumed that all existing power lines in the target grid can be further expanded. A grid expansion potential was not assumed for new corridors (i.e. a “new construction” as defined in the NEP). This simplified assumption is reasonable since it is not the task of the present study to make statements about the exact grid expansion needs or about any power line routes that might result. Rather, the future grid expansion needs are estimated solely to gauge their approximate scope and to compare the effects of the different expansion paths of the renewable energy generation.

5 Specification of scenarios for expansion of electricity generation based on renewable energies

The analyses in this study are based on two scenarios that have substantially different basic assumptions for the expansion of electricity generation based on renewable energies. These very different assumptions are explained in the following:

- The highly dynamic cost and technological developments in renewable electricity generation have led over time to strong changes in expectations of future electricity generation from renewables (e.g. from biomass or solar energy). Corresponding developments, also as regards "flexibility options" (demand flexibility, storage, etc.), cannot be ruled out in the future; they also cannot be projected with great certainty.

- The future development of renewable electricity generation from a niche to a clearly dominant segment of the electricity system faces a number of new challenges and drivers. Restrictions may result from land availability or the need for expanded grid infrastructures. Furthermore, changes in social preferences can also play a role (trend towards self-consumption, regional supply models, etc.). From today's perspective, such challenging developments can only be robustly limited in part.

Against this background, two prototypical scenarios[16] were developed for the model analyses. These scenarios have very different perspectives and development paths:

- The *energy transition reference* scenario describes a development that is currently assumed in mainstream projections of future developments. The expansion of the renewable power plant fleet and system integration are primarily geared to economic efficiency and, from the view of power plant operators, optimum site selection. As a result, a larger share of onshore wind plants is located in the north of Germany and fewer PV systems are installed. However, higher power transmission needs tend to be expected for such a climate protection path, which can affect the grid expansion needs.

16 The two scenarios represent two different development patterns; by no means do they exhaust, however, the possibilities that can be estimated based on currently known technologies. Another path could, for example, be based on the significantly stronger expansion of offshore wind power plants. Such a scenario, which could not be analyzed in detail within the scope of this study, requires further analysis.

- » The *solar focus* scenario, assumes a development that is more strongly geared to decentralized electricity generation based on renewable energies. It assumes a very high share of decentralized PV systems. Significant shares of these systems are designed for self-consumption, which lead to changed needs and strategies for the use of flexibility options (storage, etc.) in the course of micro-optimization. This means that the construction of renewable energy plants will have to be increasingly concentrated in the south and west of Germany. Since the energy yields of wind power plants are lower and those of PV are higher in the south, there is a substantially stronger emphasis on expanding the use of roof-mounted PV systems. From the second half of the 2020s, therefore, the expansion of onshore wind energy substantially levels off after a phase of continued dynamic expansion. As such, only the power plants shut down for age-related reasons are replaced with modern ones with the same overall capacity. Only after 2040 is it necessary to expand onshore wind power again, due to huge increases in electricity demand. Typically, lower grid expansion needs are expected for development patterns of the electricity system that have a lower expansion of wind power.

Figure 5-1: **Expansion of electricity generation capacities based on solar and wind energy in Germany, 2020–2050**

Source: Öko-Institut

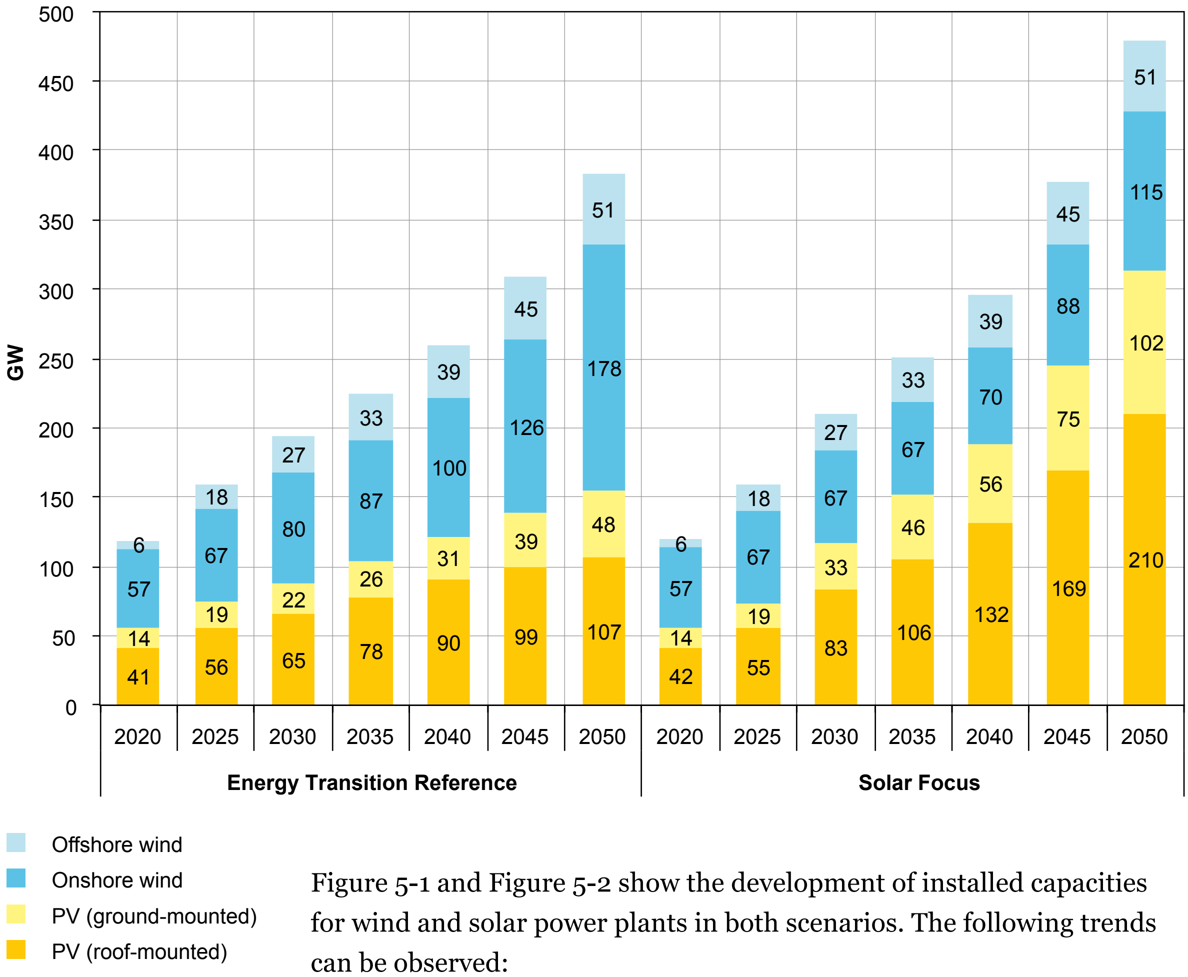


Figure 5-1 and Figure 5-2 show the development of installed capacities for wind and solar power plants in both scenarios. The following trends can be observed:

» Up to 2020, the installed capacities for wind and solar power are identical in the two scenarios. Compared to 2015, PV systems with a total capacity of approx. 16 GW are put into operation, with a net addition of 16 GW for onshore wind plants, and approx. 3 GW for offshore wind plants.

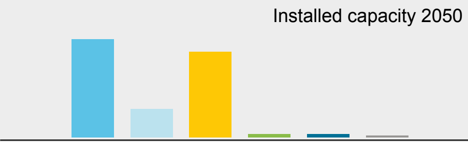
» In the *energy transition reference* scenario, the net capacity of roof-mounted PV systems increases by 24 GW and that of ground-mounted PV systems by 8 GW in the decade from 2020 to 2030. In the *solar focus* scenario, the installed capacity of roof-mounted systems increases by 41 GW and that of ground-mounted PV systems by 19 GW over the same period. The capacities of onshore wind power plants in operation increase by 23 GW in the *energy transition reference* scenario and by

Figure 5-2: **Electricity generation capacities based on solar and wind energy in Germany, 2015, 2035 und 2050**

Source: Öko-Institut

Scenario 1: ENERGY TRANSITION REFERENCE

Scenario focused on expanding wind power plants based on spatial distribution assumptions in Scenario B 2035 of NEP

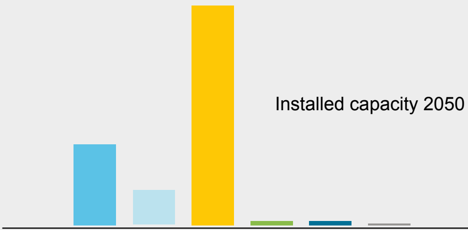


	Onsh. wind	Offsh. wind	PV	Biomass	Hydro	Rest	Total
2050	178	51	154	6	6	1	396
2035	87	33	105	6	6	1	237
2015	41	3	39	8	6	1	99

Data in GW

Scenario 2: SOLAR FOCUS

Scenario with a focus on decentralized expansion of PV in load centres and moderate expansion of wind power



	Onsh. wind	Offsh. wind	PV	Biomass	Hydro	Rest	Total
2050	115	51	313	6	6	1	492
2035	67	33	151	6	6	1	264
2015	41	3	39	8	6	1	99

Data in GW

only approx. 10 GW in the *solar focus* scenario.[17] In both scenarios, the increased net capacity of offshore wind energy is 20 GW. In 2030 the share of solar power in the total variable electricity generation capacity is 45% in the *energy transition reference* scenario and 55% in *solar focus*. Due to the lower annual utilization of PV systems, the total installed power plant capacity (including demand flexibility, etc.) is approx. 16 GW or 6% higher in the *solar focus* scenario than in the *energy transition reference* scenario.

» Between 2030 and 2040, the net capacity of roof-mounted PV systems in the *energy transition reference* scenario increases by a further 25 GW and that of ground-mounted PV systems by 9 GW. In the *solar focus* scenario, the installed capacity of roof-mounted PV systems increases by 48 GW and that of ground-mounted PV by a further 23 GW over the same period. The net increase in onshore wind power plants is

17 To enable appropriate classification of these, it should be noted that the additional capacities stated here are net capacities. In order to achieve this net expansion, additional capacity must also be installed to replace the capacity of onshore wind power plants shut down for age-related reasons. In the period from 2020 to 2030 it is to be expected that an additional annual expansion of approx. 2 GW is needed in order to maintain a constant onshore wind capacity.

20 GW in the *energy transition reference* scenario and approx. 2 GW in the *solar focus* scenario. In the latter scenario, almost only those power plants shut down for age-related reasons are replaced (approx. 4 GW annually). In both scenarios, the installed capacity of offshore wind power plants increases by a further 12 GW. In 2040, the share of solar power plants in the total variable power generation capacity is 47% in the *energy transition reference* scenario and 63% in the *solar focus* scenario. Due to the different utilization of PV and wind power plants, the total installed power plant capacity (including demand flexibility, etc.) in the *solar focus* scenario is about 36 GW or 10% above the level in the *energy transition reference* scenario.

» From 2030 to 2040, the net capacities of roof- and ground-mounted PV systems each increase by 16 GW in the *energy transition reference* scenario. In the *solar focus* scenario the net installed capacity of roof-mounted PV systems increases by 79 GW, while that of ground-mounted systems increases by 46 GW. In the context of substantially increasing (direct and indirect) electricity demand in the transport and heat sector, onshore wind power capacity increases by 78 GW (net) in the *energy transition reference* scenario and by approx. 46 GW (net) in the *solar focus* scenario. In both scenarios, the installed capacity of offshore wind power increases by 12 GW. At the end of the scenario time frame, the share of solar power plants in the total variable power generation capacity is 40% in the *energy transition reference* scenario and 65% in the *solar focus* scenario. Due to the different annual generation from PV and wind power plants, the total installed power plant capacity (including demand flexibility, etc.) is approx. 96 GW or 20% higher in the *solar focus* scenario than in the *energy transition reference* scenario.

» The capacity developments of electricity generation from other renewable energy sources (hydro, biomass, geothermal) do not differ for the scenarios. Furthermore, the installed capacity of hydro power plants does not change over time, while the installed capacity of biomass power plants decreases by approx. one third to 6 GW by 2030. The latter can be attributed to increased demand for biomass from other sectors, the cost situation and the very limited potentials of sustainable biomass. After 2030 it remains at this level until the end of the scenario period.

In the *energy transition reference* scenario, the installed capacity of roof-mounted PV systems thus increases to 65 GW by 2030, 90 GW by 2040 and 107 GW by 2050 overall. In the *solar focus* scenario, the corresponding capacity levels are 83, 132 and 210 GW, respectively, with the result that the theoretically exploitable rooftop area potentials have been extensively tapped by the end of the scenario period.

For ground-mounted PV systems, the electricity generation capacity in the *energy transition reference* scenario increases to 22 GW by 2030, 31 GW by 2040 and 48 GW by 2050. The corresponding levels in the *solar focus* scenario are 33, 56 and 102 GW, respectively.

In the *energy transition reference* scenario, the capacity of onshore wind power plants amounts to 80 GW by 2030, 100 GW by 2040 and 178 GW by 2050. This scenario therefore comprises a net increase of 2.5 times the currently installed capacity for onshore wind. By contrast, the installed capacity of onshore wind power plants in the *solar focus* scenario is 67 GW for 2030, 70 GW for 2040 and 115 GW at the end of the scenario period. In the latter scenario, the net capacity of the current fleet of onshore wind power plants expands by a factor of 1.25.

The capacity of the offshore wind power plant fleet amounts to 27 GW in 2030 in both scenarios and increases to 39 GW by 2040 and to 51 GW by 2050. By 2050, then, there is almost a tenfold increase of the currently installed capacity of offshore wind power.

The complete dataset for installed power plant capacities for the different generation options for Germany is provided in aggregated form in Annex 1. It includes the generation, storage and demand-side capacities necessary to ensure security of supply. The regional distribution of wind and solar power plants is discussed in the following sections.

6 Regionalization of wind and PV power generation

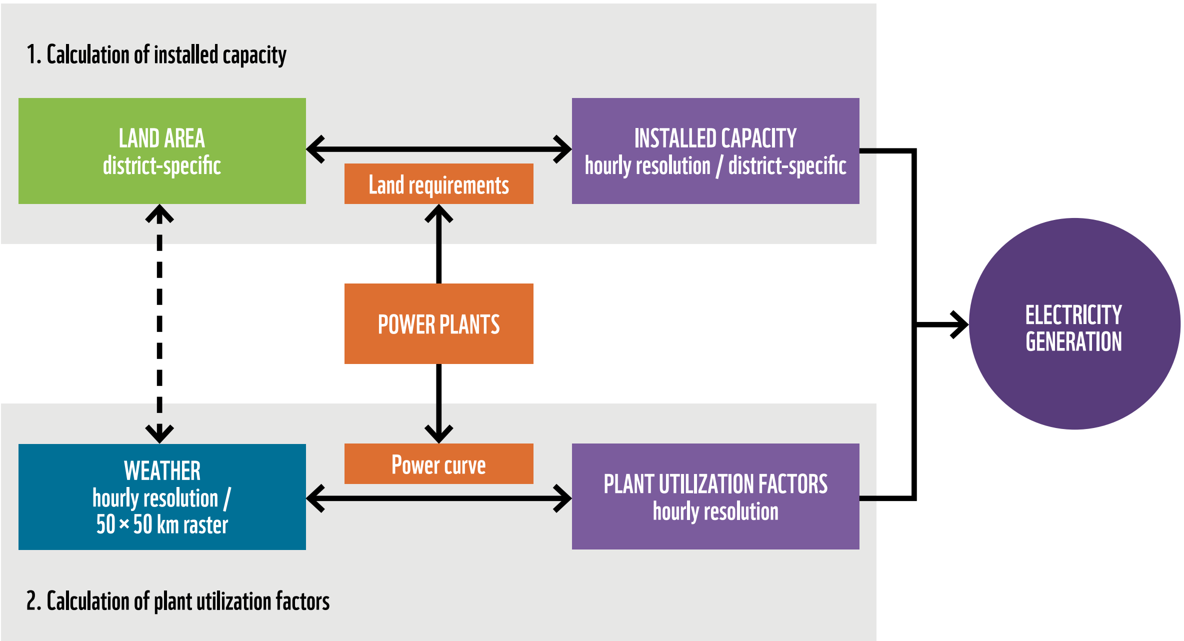
6.1 Methodological approach

For the modelling district-specific feed-in time series were developed for the fluctuating renewable power generation technologies. Based on the year- and state-specific scenarios for the growth of renewable energies elaborated in chapter 5, Prognos produced the feed-in time series in hourly resolution for each district for onshore wind power, offshore wind power[18], roof-mounted PV and ground-mounted PV.

The analyses are divided into two steps: firstly, the installed capacity is calculated for each district; secondly, the hourly power plant utilization factors are calculated. These two values are then used to determine the district-specific electricity generation data in hourly resolution for each technology under consideration.

Figure 6-1: Methodology for calculating electricity generation from renewable energies

Source: Prognos



18 Offshore wind power plants were assigned to the districts in which the corresponding offshore cable connections feed the electricity into the grid.

Figure 6-1 shows the methodology used for the calculations. The following sections discuss the technology-specific particularities in detail. To calculate the installed capacity by district, the technology used in the simulation and the land availability by district are the most relevant aspects. The power plant technologies and the regional wind and solar availability are used to calculate the plant utilization factors. The area-related specifications and the predominant energy available in that area are fundamentally interdependent.

6.2 Calculation of installed capacity
6.2.1 Assumptions relating to land availability

Due to environmental and acceptability-related restrictions, land availability for electricity generation based on renewable energies – particularly for onshore wind power and for ground-mounted PV systems – is a key parameter in implementing energy transition. Germany has a total land area of approx. 357.6 thousand square kilometres (km^2) (Destatis & Statistische Ämter des Bundes und der Länder 2018). Residential and transport areas account for approx. 13%, agricultural areas for 52%, wooded areas for 30%, and water areas for 2% of the total land area. The transformation of the electricity system to one based on renewable energies brings about a new (economic) category of use; consequently, electricity generation based on renewable energies competes with established land uses for the same areas. Onshore wind energy competes primarily with residential buildings as well as nature conservation and environmental protection areas. To ensure that energy transition is implemented in a way that is compatible with nature and the environment, it is of the utmost importance that the land use for power generation remains within a sustainable framework and that other uses are not unduly impaired.

Although the following analyses are based on the metric of "land use", it should be noted that the process of land use change is always behind this metric. These land use changes can take very different forms. In the case of wind power plants, for example, changes are often made only to the foundations and for building the necessary pathways; for the remaining land, there are only minor or no changes in use. In the case of ground-mounted PV systems, changes are made to a much larger part of the total area concerned. It should be taken into account that the above-mentioned land use changes can have very different implications; in some cases, they can have a positive effect on, for example, biodiversity (e.g. biotope developments resulting from ground-mounted PV systems). However, these aspects can only be taken into account in specific plans;

on an aggregated level, it would only be possible to use rather restrictive approaches to the availability of land to which changes can be made.

This study builds, first of all, on previous projects that determine viable frameworks for the land use needs of power generation based on renewable energies in the future:

- The “Potentials of Onshore Wind Energy” study (UBA 2013) published by the German Federal Environment Agency specifies a land use potential for electricity generation from wind energy that amounts to approx. 14% of Germany’s total surface land area. The UBA study does not, however, take into account aspects such as special conservation areas or other restrictions (e.g. radar systems). The particular restrictions to which it refers are, most notably, distance regulations for residential buildings. It estimates that 13.8% of Germany’s total land area has a minimum distance of 600 metres (m) to residential buildings. If minimum distances of 1,000 m or 2,000 m are assumed, this percentage falls to 5.6% and 0.4% respectively.

- The publicly available data set of land use potentials for onshore wind power compiled by the University of Flensburg (doi.org/10.5281/zenodo.844604) calculates that 7.6% of Germany’s total surface area is available overall.

- The results of an analysis commissioned by the German Federal Ministry of Transport and Digital Infrastructure (BMVI 2015) are more differentiated. It calculates the land use potential as ranging from 2.4% to 10.9% of Germany’s total surface area (the range results from different degrees of restrictions being applied). According to this analysis, only 1.7% of the total land area is largely free of restrictions. Thus it is available for power generation from onshore wind energy, i.e. land which does not involve the risk of conflict with other uses; in addition, approx. 1.0% of the total land area is available for ground-mounted PV systems.[19] The remaining land is classified as subject to various degrees of restrictions: it may be possible to use the land for renewable power generation, but land use competition will have to be considered on a case-by-case basis.

19 In the present study, land is classified as largely free of restrictions if, from the perspective of land use and environmental planning, no barriers to the conversion of renewable energy into electricity can be identified. For more information on this classification, see the detailed explanations in the study (BMVI 2015).

With these findings from the literature review in mind, the maximum land availability for power generation based on renewable energies was limited to a maximum of 5% of Germany's total surface area in the present study.

Based on district-specific soil data made available by the Federal Statistical Office, a top-down approach was used to regionalize the land allocation for electricity generation based on renewable energies on a district level. In a first step, all land currently being used for other purposes (settlement areas, wooded areas, water areas, peatland and heathland, mining areas and wasteland) was subtracted from the district totals. This left, for each district, agricultural land and areas of other uses that are potential areas for electricity generation. 10% of all these areas was excluded from the classification as land available for renewable power plants in order to account for further restrictions (e.g. regulations on the distance to the nearest settlement areas, nature conservation areas, infrastructures, etc). This statistical approximation results in a land potential for electricity generation based on renewable energies that amounts to, on average, a maximum of 5% of Germany's total surface area.

According to the methodology used in this study, the potentially available land for electricity generation from wind energy and ground-mounted PV systems varies by district, ranging from 0.4% to 8.2%. For the 10 districts with the lowest share of land available for this use, the area-weighted value is 0.9%. For the 10 districts with the highest shares of land available for this use, the area-weighted value amounts to 7.6%. Overall, Schleswig-Holstein, Mecklenburg-Western Pomerania and Saxony-Anhalt have the largest land availability for wind and solar power generation. In these states an average of 6.7% to 6.1% of the total area of the state was identified as potentially usable for electricity generation based on renewable energies. In absolute terms, Bavaria, Lower Saxony and North Rhine-Westphalia have the largest land availability potentials overall (see Table 6-1).

Table 6-1: **Potential land availability for onshore wind energy and ground-mounted PV**

Source: Calculations by Prognos based on Destatis (2016)

	Surface area	Settlement and traffic areas	Peatland and heathland	Wooded areas	Water areas	Mining and wasteland	Areas for energy conversion	Share of total surface area
	km²							
Baden-Württemberg	35,677	5,158	30	13,678	390	259	1,616	4.5%
Bavaria	70,055	8,399	151	25,721	1,235	2,133	3,291	4.7%
Brandenburg*	30,546	3,426	127	10,698	1,082	691	1,452	4.8%
Hesse	21,115	3,324	2	8,488	295	128	888	4.2%
Mecklenburg-Vorpommern	23,213	1,902	45	5,086	1,445	291	1,444	6.2%
Lower Saxony*	48,036	6,896	719	10,541	1,162	848	2,787	5.8%
North Rhine-Westphalia	34,113	7,828	69	8,878	662	262	1,641	4.8%
Rheinland-Pfalz	19,848	2,836	2	8,399	271	85	826	4.2%
Saarland	2,569	538	1	874	25	23	111	4.3%
Saxony	18,449	2,432	28	5,033	427	462	1,007	5.5%
Saxony-Anhalt	20,452	2,248	141	5,069	479	109	1,241	6.1%
Schleswig-Holstein*	16,558	249	118	1,728	869	274	1,108	6.7%
Thuringia	16,202	1,588	2	53	203	231	888	5.5%
Total	**357,327**	**49,066**	**1,437**	**109,493**	**8,543**	**5,797**	**18,299**	**5.1%**

Note: * The city states were integrated in the totals for the surrounding federal states: Berlin in Brandenburg, Bremen in Lower Saxony, and Hamburg in Schleswig-Holstein.

6.2.2 Assumptions relating to power plant technologies

In line with the overarching aim to demonstrate the feasibility and consequences of the transition to a sustainable energy supply, the land use analyses in this study are based on conservative assumptions for technology development. Thus, the power plant technologies considered available for use in the future are those available at present and those foreseeable in the near future. These assumptions do not reflect long-term developments that could occur, with their corresponding uncertainties. For each technology, two central assumptions about land use are made based on various assumptions relating to future development. Firstly, the land use

Tabelle 6-2: **Potential land availability for onshore wind energy and ground-mounted PV**

Source: Prognos

Technology	Land use	
	Current	Expansion
	m²/kW	
Onshore wind power		
strong wind turbine (Ø > 7.5 m/s)	49	45
weak wind turbine (Ø < 7.5 m/s)	59	78
Offshore wind power	125	62.5
Roof-mounted PV	7	6
Ground-mounted PV	17	17

of the existing power plant fleet is calculated. Secondly, the land use for the expansion of the power plant fleet is estimated. With a view to land use for onshore wind power, a distinction was made between strong and weak wind turbines; districts were assigned a type of turbine based on average wind speeds. Table 6-2 shows the assumptions for the land use of the different technologies.

The land use of Germany's current power plant fleet is calculated using data on existing power plants, on power plant manufacturers' data on their dimensions and on the typical power plant configurations (e.g. the regulation that provides for a distance of 5 rotor diameters in the main wind direction and 3 rotor diameters in the secondary wind direction). For the sake of simplicity, a single value instead of an annual development of land use by technology is assumed for the expansion. Particularly in the case of offshore wind power, a sharp decrease in development from the current level was assumed. Weak wind turbines tend to be equipped with larger rotor diameters for more continuous use of wind resources, which results in increased land use in future.

6.2.3 Assumptions regarding the expansion logic

The land requirements of the power plants and the available land by district are taken into account in estimating the development of installed capacity by district. Using the master data on power plants for the conversion of renewable energies up to 2015 provided by the German Solar Energy Society (http://www.energymap.info), a basic distribution of these power plants at district level was mapped.

The districts were subsequently classified according to their attractiveness in order to establish a sequence for expanding the power plant fleet. The attractiveness of the districts varies depending on the technology. The following formulas were used to conduct a quantitive assessment of the attractiveness of each district:

$$\textit{Attractiveness}_{\textit{onshore wind power}} = \textit{wind potential}$$

$$\textit{Attractiveness}_{\textit{roof-mounted PV}} = \frac{\textit{demand in 2050 + solar potential}}{\textit{installed wind capacity in 2050}}$$

$$\textit{Attractiveness}_{\textit{ground-mounted PV}} = \frac{\textit{available area + demand in 2050 + solar potential}}{\textit{installed wind capacity in 2050 + installed roof PV capacity}}$$

Each district is assigned an attractiveness value using this methodological approach. A normal distribution with a uniform variance is assumed, resulting in a range of attractiveness by district. These ranges overlap, with the result that there is a mixture of districts in the attractiveness classification of the sites. With the help of this distribution function, the annual quantities of the expanded power generation specified in the scenarios are distributed taking into account the area restrictions.

In the *energy transition reference* scenario, an expansion was assumed only within the scope of state-specific guidelines in order to allow for the expansion specifications of Germany's Grid Development Plan for Electricity (NEP) in the different states. In the *solar focus* scenario, the state-specific guidelines for onshore wind energy were used. The PV systems were distributed using the above-mentioned indicators.

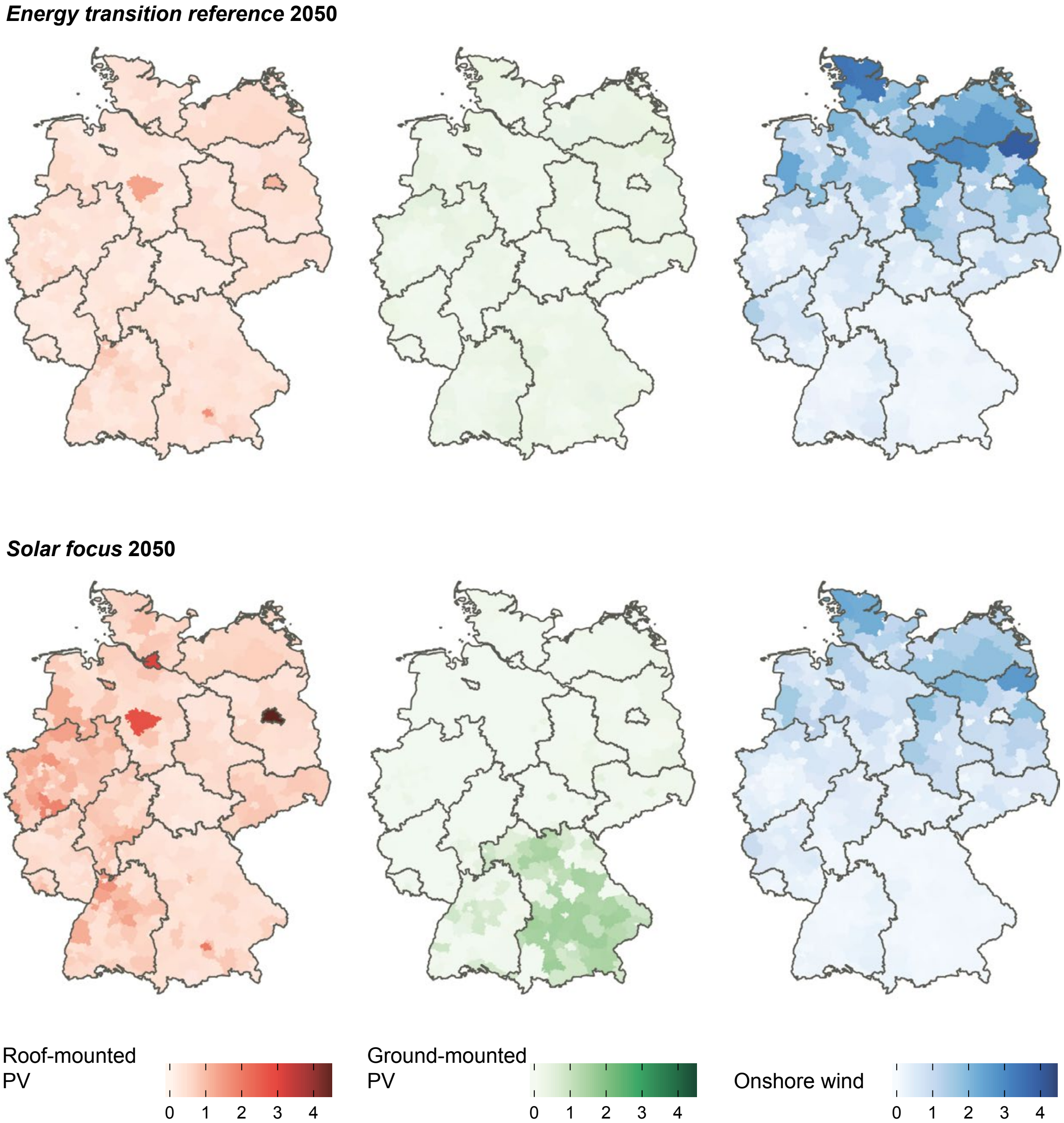
6.2.4 Installed capacity

Using the methodology described above, two prototypical, district-specific expansion paths were developed for onshore wind energy, offshore wind energy, roof-mounted PV and ground-mounted PV (Figure 6-2 and Table A-3 in Annex 2). As explained in chapter 5, the installed capacity was determined in such a way that fulfilment of electricity demand is ensured. In the simulation at district level there are, in a few cases, slight deviations between the structure of electricity generation and the installed capacity by district calculated using the expansion algorithm. These are due to the fact that the algorithm is based on the electricity quantity generated and not on the capacity to be installed. The slight differences can be traced back to the district-specific expansion algorithm containing a more precise value for expansion during the year and for regional weather conditions.

On state level the *energy transition reference* scenario is based on the values for installed capacity in the NEP for wind power and PV. These values were extended after 2035 in order to ensure that the electricity demand is met by renewable sources up to 2050. The scenario shows in particular a strong expansion of onshore wind energy. By 2050 178 GW of installed capacity of onshore wind energy is needed overall, in addition to 51 GW of installed capacity of offshore wind energy and 155 GW of installed PV capacity.

The highest installed capacities of onshore wind energy in 2050 are in Lower Saxony (37 GW), Brandenburg (26 GW) and Schleswig-Holstein (23 GW). The lowest installed capacity levels for wind energy in 2050 were calculated for Saarland (1 GW) as well as Baden-Württemberg, Saxony and Thuringia (6 GW each). The expansion by district ranges from 2 MW to 3.9 GW, with an average value of approx. 442 MW of installed capacity per district. In the most-developed 10% of the districts, approx. 46% of the total wind power plant capacity is concentrated. Less than 0.2% of the total wind power plant capacity is located in the least-developed 10% of the districts.

Figure 6-2: **Distribution of installed capacity (GW) for onshore wind energy, roof- and ground-mounted PV systems by district, 2050**
Source: Prognos



The same assumptions were used for the installed capacities of offshore wind energy in the *energy transition reference* scenario and the *solar focus* scenario. In 2050, the installed capacity of offshore wind energy amounts to 44 GW for the North Sea and 7 GW for the Baltic Sea, independently of the scenarios. Approx. 33 GW of the installed capacity in the North Sea are connected to the extra-high voltage grid in Lower Saxony; the remaining 11 GW are connected via Schleswig-Holstein. The grid connections of all power plants in the Baltic Sea are located in Mecklenburg-Western Pomerania.

In 2050 roof-mounted PV systems are mainly located in Bavaria (27 GW), North Rhine-Westphalia and Baden-Württemberg (15 GW each). The lowest installed capacities for roof-mounted PV were calculated for Saarland (1 GW), Thuringia and Mecklenburg-Western Pomerania (3 GW each). The capacity expansion by district ranges from 24 MW to 1.6 GW, with an average value of 265 MW. Approx. 23% of the total roof-mounted PV capacity is concentrated in the most-developed 10% of the districts (predominantly in urban areas); approx. 3% of the total roof-mounted PV capacity is located in the least-developed 10% of the districts.

The installed capacity of ground-mounted PV systems is located predominantly in Bavaria (12 GW) and to a lesser extent in North Rhine-Westphalia and Baden-Württemberg (6 GW each) in 2050. All other states have low installed capacities of 1 GW to 5 GW. The capacity expansion by district ranges from 24 MW to 1.6 GW, with an average value of 265 MW. In 2050 approx. a quarter of the total ground-mounted PV capacity operated in Germany is located in the most-developed 10% of the districts; approx. 0.5% of the total ground-mounted PV capacity is located in the least-developed 10% of the districts.

The *solar focus* scenario involves a stronger expansion of photovoltaics in southern and western Germany. The capacity of onshore wind energy was reduced compared to the *energy transition reference* scenario overall; the proportionate spatial distribution, which was based on the Grid Development Plan, was retained. The potentials for roof-mounted PV are exhausted by 2050. The distribution of these power plants is pre-defined by roof area distribution. In contrast to the *energy transition reference* scenario, a particularly large proportion of roof-mounted PV is installed in North Rhine-Westphalia and in Lower Saxony since large roof areas are available in those states, although they have lower yields than the ones on sunnier roof areas in Bavaria and Baden-Württemberg. Ground-mounted PV is expanded particularly in Bavaria, taking into account the land availability, yield, demand and a counterbalancing, complementary expansion compared to other technologies.

The distribution of onshore wind energy was reduced overall to 115 GW, but the relative distribution across the German federal states in the *energy transition reference* scenario was retained. As a result, the states of Lower Saxony (24 GW), Brandenburg (17 GW) and Schleswig-Holstein (15 GW) have the highest installed capacities. The lowest installed capacities are in Saarland (1 GW) as well as Baden-Württemberg, Saxony and Thuringia (approx. 4 GW each). The expansion by district ranges from 1 MW to 2.5 GW, with an average installed capacity per district of approx. 286 MW. Approx. 46% of the total onshore wind power plant capacity is located in the most-developed 10% of the districts; less than 0.2% of the total onshore wind power plant capacity is located in the least-developed 10% of the districts.

The maximum potential for roof-mounted PV is completely exhausted by 2050, with an installed capacity of 210 GW. This installed capacity is situated above all in North Rhine-Westphalia (44 GW), Bavaria (34 GW) and Baden-Württemberg (28 GW). The lowest installed capacities for roof-integrated PV are in Saarland (3 GW), Mecklenburg-Western Pomerania (4 GW) and Thuringia (5 GW). The expansion by district ranges from 75 MW to 4.4 GW, with an average value of 523 MW per district. About a quarter of the total capacity of roof-mounted PV is situated in the most-developed 10% of the districts (predominantly in urban areas). Approx. 3% of the total capacity of roof-mounted PV is situated in the least-developed 10% of the districts.

Ground-mounted PV systems are very strongly concentrated in Bavaria (72 GW) and Baden-Württemberg (12 GW) in 2050. All other German states show low installed capacities of 1 GW to 3 GW. The expansion by district ranges from zero to 1.6 GW, with an average value of 254 MW. The concentration of ground-mounted PV is substantially higher in the *solar focus* scenario than in the *energy transition reference* scenario: approx. 52% of the total ground-mounted PV capacity is concentrated in the most-developed 10% of the districts; approx. 0.05% of the total ground-mounted PV capacity is located in the least-developed 10% of the districts.

6.2.5 Land use

Land use for the installed capacity of renewable electricity generation is of central importance to energy transition. The development path of energy transition – i.e. the choice of technologies used, the dependence on imported electricity or carbon-neutral fuels – fundamentally depends on the land available in Germany for the building of renewable energy power plants. The development paths produced by the *energy transition reference* scenario and the *solar focus* scenario have different land use needs in their designs for transforming the energy system.

An analysis of land use is conducted for all renewable technologies. Only the land use needs of onshore wind power and ground-mounted PV systems in the scenarios are considered here. These could potentially be erected on the same land identified as available; they therefore compete for land use.

In calculating the land use needed, it was assumed that either a wind power plant or a ground-mounted PV system is to be erected on the land. The – theoretically possible – combined use of the same land for onshore wind power plants and ground-mounted PV systems was not considered. The calculated land use needs thus represent a conservative estimate at the upper end of the range.

The land needed for electricity generation from offshore wind energy are not further analyzed here. The reasons for this are, firstly, there is no competition for land use from other renewable technologies; secondly, the installed capacity is the same for both scenarios; and, thirdly, land use is not a useful parameter for considering the main limitations and restrictions relevant to the building of offshore power plants. No new land use arises for roof-mounted PV systems and there is no land use competition from other sources of renewable electricity generation.

Overall, the following land uses result for onshore wind power and for ground-mounted PV systems in the two scenarios:

1. The land use in the *energy transition reference* scenario is as follows:

- in 2035 approx. 1.2% of the land area is used for onshore wind power plants and approx. 0.1% for ground-mounted PV systems; and
- in 2050 approx. 2.3% of the land area is used for onshore wind power plants and approx. 0.2% for ground-mounted PV systems.

2. The land use in the *solar focus* scenario is as follows:

- in 2035 approx. 1.0% of the land area is used for onshore wind power plants and approx. 0.2% for ground-mounted PV systems; and
- in 2050 approx. 1.5% of the land area is used for onshore wind power plants and approx. 0.5% for ground-mounted PV systems.

With regard to the spatial differentiation of ground-mounted PV systems and onshore wind power plants which compete for land use, the largest land use in the *energy transition reference* scenario occurs in Lower Saxony, Brandenburg, Saxony-Anhalt and Schleswig Holstein in 2050. The largest land use for ground-mounted PV systems and onshore wind power plants occurs – relative to their total surface areas as states – in Schleswig-Holstein, Saxony-Anhalt and Brandenburg. The areas needed for these technologies account for 6.2%, 5.4% and 4.3% of the total areas of the respective states. Bavaria, Baden-Württemberg and Saxony have the lowest areas needed, with values amounting to 0.9%, 1.2% and 1.6% of the total area of the state respectively.

With a view to the spatial distribution patterns for onshore wind power plants and ground-mounted PV systems, the largest land use in the *solar focus* scenario occurs in Lower Saxony, Brandenburg, Saxony-Anhalt and Schleswig-Holstein in 2050. The absolute values are more than one third below those of the *energy transition reference* scenario. The largest land use for onshore wind power plants and ground-mounted PV systems occurs – relative to their total surface areas as states – in Schleswig-Holstein, Saxony-Anhalt and Brandenburg. However, the land use of these states, which amounts to 4.1%, 3.6% and 2.8% respectively for 2050, is below that of the *energy transition reference* scenario. The lowest specific land use arises for Baden-Württemberg, Saxony and Hesse (1.1% each).

It should be noted that in the *solar focus* scenario – in an ambitious assumption – the land potential for roof-mounted PV systems is completed exhausted.

The land use of technologies competing for onshore land use amounts to 2.5% of Germany's surface land area in the *energy transition reference* scenario and to 2.0% in the *solar focus* scenario. Both values are below the maximum land potentials that were calculated bottom-up as a basis for the analysis.

In comparison to other limits, both scenarios also lie within the identified limits for land use compatibility. However, the study commissioned by the German Federal Ministry of Transport and Digital Infrastructure on available onshore land potentials (BMVI 2015) shows a largely restriction-free land use potential of only 1.7% for onshore wind power and 0.9% for ground-mounted PV systems. In the *energy transition reference* scenario, land use for onshore wind energy slightly exceeds 1.7% of Germany's total surface area that the above study identified as largely without restrictions and makes use of land identified in BMVI (2015) as subject to soft restrictions (an additional land potential of approx. 0.7% is calculated for this, giving rise to an overall potential of 2.4%). The land needed for onshore wind power in the *solar focus* scenario and for ground-mounted PV in both scenarios remain within the above-mentioned limits.

Three aspects should be highlighted for the purposes of classification:

» The land use needs calculated in the present study constitute a conservative estimate since the combined use of the same land for wind and solar power generation is not taken into account. The nature- and landscape-friendly use of land potentials for onshore wind energy and ground-mounted PV always occurs in the field of tension between competing land uses and social acceptability.

» The land use needs for renewable power generation (presumed to be the "most recent" use of land) are not the only land uses requiring legitimation – all "traditional" land uses also require legitimation. A change in previous land use for economic activities (settlements, infrastructures, agriculture, etc.) can open up additional space for renewable energy use, possibly as part of economic value chains, without compromising nature conservation and environmental protection. It should also not be forgotten that the land use changes taking place in the course of energy transition can be classified, at least in some cases, as part of the process of constantly changing cultural landscapes.

» Land use for renewable electricity generation can also be extended to areas beyond those considered largely free of restrictions. The land potentials with soft restrictions are not fully exploitable, but they can be significantly tapped if well-designed combined uses (e.g. agriculture and ground-mounted PV) are realized on a case-by-case basis.

Although additional land use needs for the transformation of the electricity system are likely to play a minor role quantitatively and qualitatively, it should be pointed out that only the land use needs of onshore wind power and ground-mounted PV were considered in the present study. The land use needs for expanded grid infrastructures, for example, have not been analyzed.

Finally, it should also be taken into account that the (total) land use in Germany that is compatible with nature may fall short of the possibilities for climate protection. The resulting land use conflicts require social and political resolution.

6.3 Calculation of regionalized electricity generation

6.3.1 Preliminary remarks

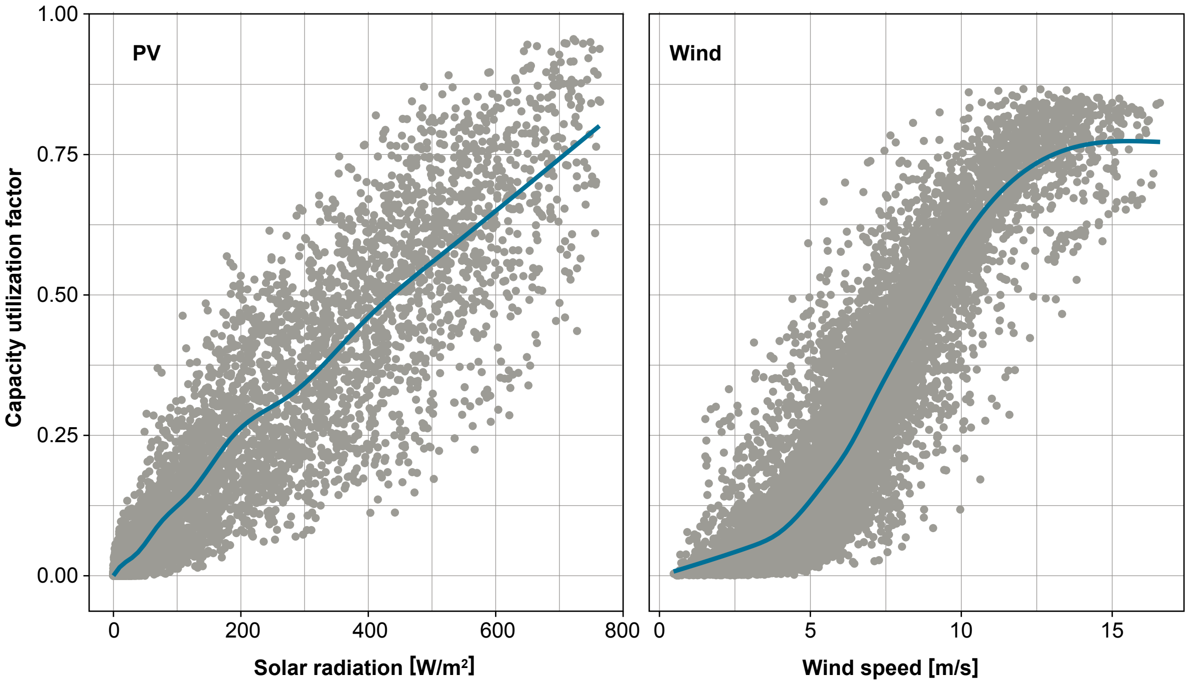
In the present study the electricity generation from renewable energies per district is calculated based on power plant distribution per district. Using the data on solar radiation and wind speed provided by NASA (https://gmao.gsfc.nasa.gov/reanalysis/merra-2/), the hourly primary energy supply per district is calculated. With the help of power curves, a function is assigned to the power plants per district and per technology. This determines the hourly capacity utilization that can be achieved using the primary energy supply prevailing in specific hours (also called capacity utilization factors). By multiplying the hourly capacity utilization factors by the installed capacity per hour and district, the feed-in time series are determined for the various technologies.

6.3.2 Power curves

The hourly electricity feed-in is calculated based on district-specific data using estimations from power curves for the different power plant fleets.

Figure 6-3: **Estimated power curves of PV and wind power plants**

Source: Prognos



The empirical feed-in time series of transmission system operators are assigned to the corresponding weather data in order to calculate the power curve of the power plant fleet.[20]

The power curves are adapted in respect of time and space to take into account relevant technological developments and differences. Based on the German Federal Network Agency's annual publications on the German Renewable Energy Sources Act (BNetzA 2017), the power curves are subdivided regionally and calibrated against historical data. Technical developments are expected to lead to higher capacity factors, which have been taken into account in the generated time series of the scenarios. Conservative developments were also assumed here.

Table 6-3: **Development of annual loads of different technologies**

Source: Prognos

	2015	2030	2050
		h/a	
Roof-mounted PV	880	880	880
Ground-mounted PV	1,000	1,015	1,050
Onshore wind	1,650	2,050	2,200
Offshore wind	2,500	4,040	4,250
Run-of-river hydro	6,930	6,690	6,690

Table 6-3 shows the central assumptions for the development of the full load hours of Germany's total power plant fleet by technology. Strong growth is expected in wind power in particular. The full load hours of offshore wind power are currently well below the realisable potential due to fleet failures and curtailment.

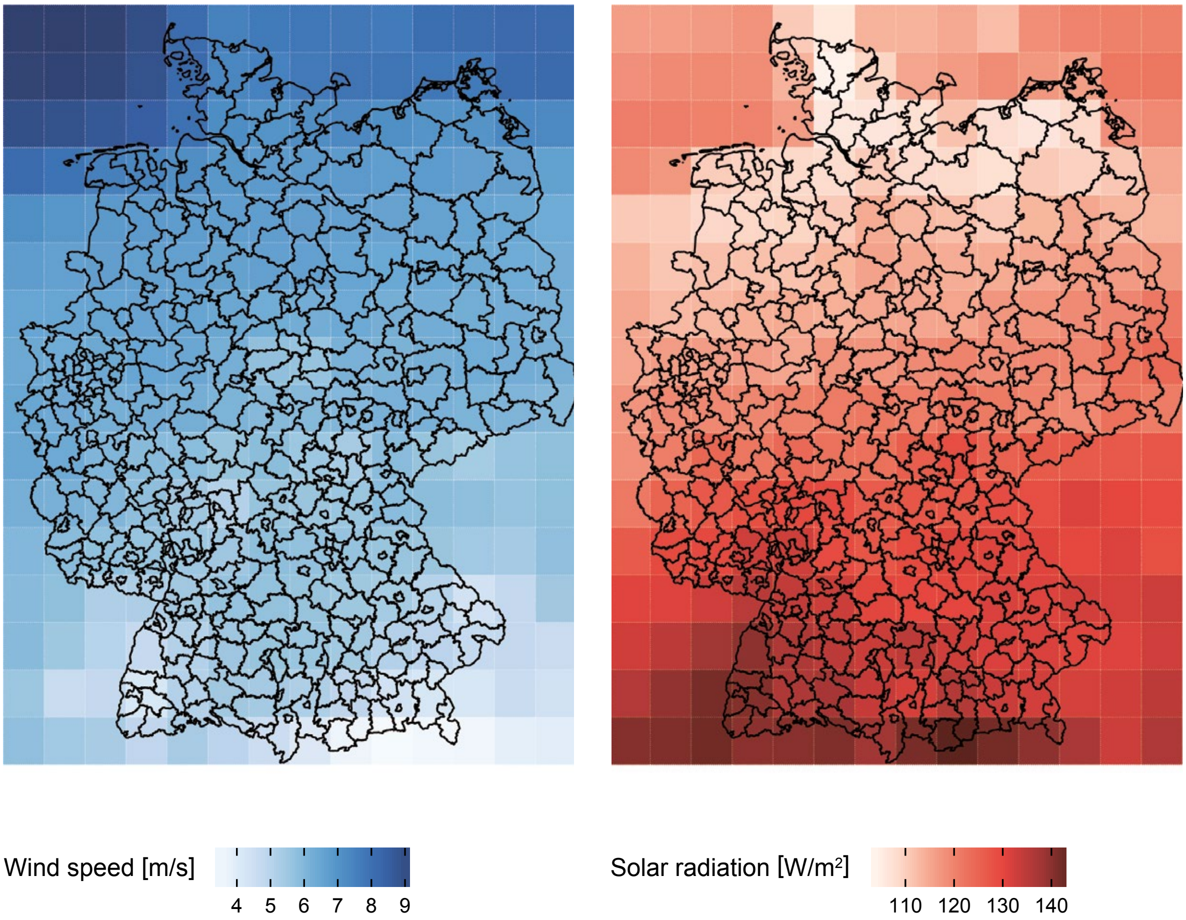
20 An alternative method for estimating the hourly electricity feed-in is to base calculations on power curves provided by power plant manufacturers. These power curves reflect power plant operation under ideal conditions, however, and do not incorporate effects such as mutual shading or local wind conditions.

6.3.3 Weather data

The data set “Modern-Era Retrospective Analysis for Research and Applications” (MERRA) provided by NASA (https://gmao.gsfc.nasa.gov/reanalysis/merra-2/) was used to calculate the primary energy supply. The MERRA dataset contains data on wind speeds at an altitude of 50 metres, soil conditions and solar radiation. The resolution is approx. 50 km × 50 km and is transferable to the district level.

Figure 6-4: **Raster data on wind speeds and solar radiation**

Source: Prognos, authors’ own diagram using NASA’s MERRA data



Average hourly values for solar radiation and wind speeds at an altitude of 50 m, 2012

6.3.4 Electricity generation

Subsequently the hourly electricity generation from renewable energies by district is calculated. Figure 6-5 shows the result of regionalizing the electricity generation. The time series of hourly electricity generation are aggregated to annual quantities of electricity generation per district, which gives rise to the spatial distribution of annual electricity generation in the diagram. For the sake of clarity, the electricity quantities generated by offshore wind energy are not shown.[21]

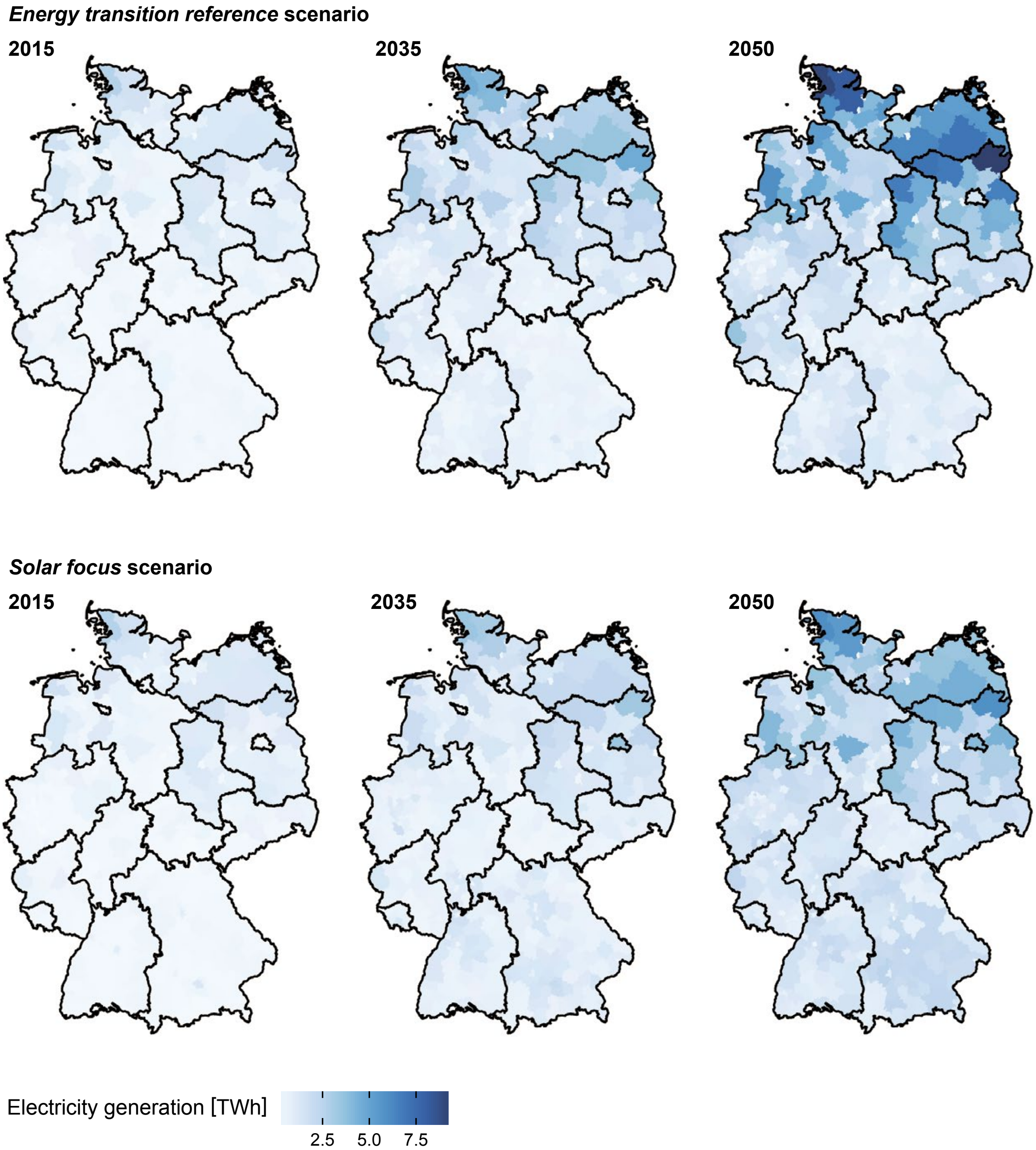
The *solar focus* scenario shows that despite a weaker expansion of wind power in the north and a stronger expansion of PV in the south and along the Rhine Valley, annual power generation from renewable energies is mainly concentrated in north-eastern Germany (Figure 6-5 and Table A-5 in Annex 2). The distribution is nevertheless more balanced in the *solar focus* scenario than in the *energy transition reference* scenario. This effect is due to roof-mounted PV being concentrated in the cities and thus in the main consumption centres; and to the stronger expansion of ground-mounted PV in Bavaria and Baden-Württemberg in the *solar focus* scenario.

For the *energy transition reference* scenario, it can be concluded that in 2050 32% of electricity generation from all four renewable technologies considered in this study occurs in Lower Saxony and 14% in Schleswig-Holstein, both of which are offshore wind regions. Each of the other federal states has a share that is lower than 10% of Germany's total renewable electricity generation. Even when offshore electricity generation is excluded, Lower Saxony accounts for 18%, Brandenburg 12% and Schleswig-Holstein 11% of the total electricity generation based on renewable energies, followed by North Rhine-Westphalia and Bavaria (10% each). The expansion of offshore technology in particular leads to a further shift of electricity generation to the north: while the share of electricity generation across all technologies increases for Schleswig-Holstein and Lower Saxony compared to today, the shares decrease for Bavaria and Thuringia and remain constant for Baden-Württemberg. When offshore electricity generation is excluded, this trend is less pronounced, but it continues to have a structural effect due to the predominant concentration of onshore wind energy in the northern regions.

21 In the districts in which offshore submarine cables are connected to the grid, the annual quantity of electricity generation is so high that it would render the distribution in the remaining districts indiscernible. The quantities are identical in both scenarios.

Figure 6-5: **Hourly electricity generation from renewable energies by district**

Source: Prognos



In the *solar focus* scenario the largest shares of electricity generation from the four renewable technologies under consideration occurs in Lower Saxony (28%), followed by Bavaria (16%) and Schleswig-Holstein (12%) in 2050. Excluding electricity generated offshore, 22% of electricity generation from PV and wind energy occurs in Bavaria, 13% in Lower Saxony and 12% in North Rhine-Westphalia. With regard to onshore wind and roof-mounted PV electricity generation, a shift to the south or (due to the high population density) to the west is observable compared to today: the share in Bavaria increases from 16% in 2015 to 22% in 2050, in Baden-Württemberg from 8% to 9%, and in North Rhine-Westphalia from 9% to 12%. For Lower Saxony, the share of electricity generation based on renewable energies decreases from 15% in 2015 to 13% in 2050.[22] In summary, then, the distribution of electricity generation based on renewable energies in the *solar focus* scenario is more balanced overall, although due to the strong regional focus of offshore electricity generation, the largest share on the state level is still in northern Germany.

22 In Figure 6-5 this trend is not clearly discernible: in Bavaria, electricity generation is distributed over significantly more districts than, for example, in Mecklenburg-Western Pomerania.

7 Modelling of electricity market and grid

7.1 Introduction and methodology

A multi-level methodology was used in the modelling of the electricity market and the electricity grid. Firstly, the PV-intensive developments, which have substantial shares of self-consumption, are calculated. Secondly, the results are calculated for the electricity production, demand and flexibility options, which remain in the market segment and are centrally coordinated via the wholesale market; and thirdly, the consequences of the market result for the expansion of the transmission grid are determined:

Phase 1: Pre-processing with optimization of PV self-consumption and regional resolution of generation and demand structures;

Phase 2: Electricity market modelling with the PowerFlex model to calculate the centrally coordinated market result (without domestic grid restrictions);

Phase 3: Regionalization of market result (for 400 nodes);

Phase 4: Load flow simulation with calculation of grid expansion needs;

Phase 5: Proceeassing and evaluation of results.

Figure 7-1: **Modelling steps**

Source: Öko-Institut

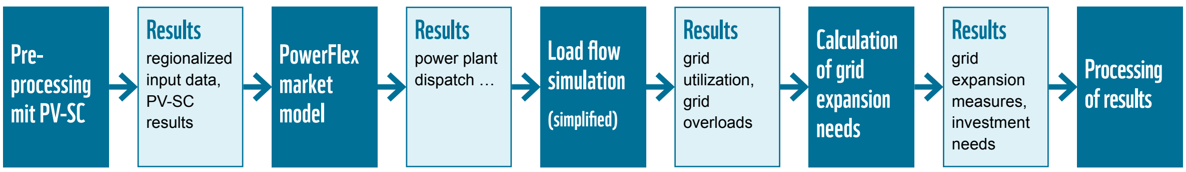


Figure 7-1 provides an overview of the modelling steps, including these different phases and the corresponding (interim) results.

7.2 Optimizing PV self-consumption

7.2.1 Preliminary remarks

The main difference between the two scenarios in this study is the technology-specific composition of the future electricity generation mix from renewable energies.

Behind this variation is the question of to what extent a focus on power generation from PV systems is beneficial for the overall system; the direct and indirect effects on the environment and human society are perceived as involving fewer conflicts. The consequences for grid expansion needs should, however, also be taken into account. The conceptual storylines and electricity quantity structures of the two scenarios are of an illustrative nature and should enable a quantitative evaluation of the different developments.

The feed-in philosophy of PV power generation plays a special role in this context. The feed-in curve from PV systems varies during the day, with power generation occurring exclusively in hours with solar radiation and with maximum production occurring around midday. With increasing shares of electricity generation from PV systems, the need for storage capacity to equalize generation and consumption patterns becomes more important.

On the electricity market an increase in the share of electricity storage conceived primarily for self-consumption in different building types and applications is currently observed. Various subsidy programmes are supporting this trend. Based on these developments, both scenarios provided for the possibility of covering part of the household demand directly on site with a self-consumption system; for this, a roof-mounted PV system is combined with battery storage, the dimensions of which are tailored to household demand.

Including PV self-consumption deviates from the cost-minimizing perspective of electricity market modelling at central level. The goal of upstream optimization is not, however, to develop an optimal cost solution for the entire electricity system, but to depict the reality of a development path induced by different framework conditions in which the fulfillment of household demand is maximized by self-consumption. Instead of making the electricity not needed at certain times available to other consumers or other regions with a demand, it is preferentially stored so that self-consumption can occur at a later time. The higher storage losses that hereby arise are taken into account. The upstream optimization of self-consumption can therefore be expected to result in reduced use of the transmission grid and a lower need for grid expansion. At the same time, the overall demand for electricity generation is expected to be higher due to the storage losses.

7.2.2 Parameters of PV systems for self-consumption

For the modelling it is assumed that, firstly, a share of the increase in roof-mounted PV systems is equipped in future with an integrated storage system to optimize self-consumption. Secondly, it is assumed that a share of the PV systems that are no longer eligible for remuneration under the German Renewable Energy Sources Act (EEG) after 20 years stay in operation for an additional five years and are equipped with a storage system for this purpose.

In both cases, a 10% share is assumed in the *energy transition reference* scenario, which remains constant from 2020 to 2050.

In the *solar focus* scenario, a constant share of 10% is assumed for the continued operation of upgraded old systems. A higher share is assumed for new PV systems equipped with a storage system: 20% in 2020 and 30% in 2025. Between 2025 and 2050 this share is assumed to remain constant at 30%.

For the *energy transition reference* scenario, this means that the number of PV self-consumption systems increases from 0.5 million to 12.5 million between 2020 and 2050. In the *solar focus* scenario, the number of PV self-consumption systems increases from 0.5 million to 25.3 million between 2020 and 2050. Table 7-1 shows the development of PV self-consumption systems for both scenarios from 2020 to 2050.

Table 7-1: PV self-consumption (PV-SC): parameters for scenarios

Source: Öko-Institut

		2020	2025	2030	2035	2040	2045	2050
Energy transition reference								
No. of storage systems	1,000	464	1,739	3,577	6,726	8,685	10,875	12,467
Storage capacity PV batteries	GW	1.7	6.5	13.4	25.2	32.6	40.8	46.8
Storage capacity	GWh	3	13	27	50	65	82	94
PV self-consumption	TWh	2.3	8.7	17.9	33.6	43.4	54.4	62.3
Total RES power generation	TWh	257	338	411	476	552	650	804
PV-SC share of RES power generation	%	1 %	3 %	4 %	7 %	8 %	8 %	8 %
Solar focus								
No. of storage systems	1,000	508	1,910	5,303	10,366	14,330	19,123	25,292
Storage capacity PV batteries	GW	1.9	7.2	19.9	38.9	53.7	71.7	94.8
Storage capacity	GWh	4	14	40	78	107	143	190
PV self-consumption	TWh	2.5	9.5	26.5	51.8	71.7	95.6	126.5
Total RES power generation	TWh	257	338	412	479	552	650	805
PV-SC share of RES power generation	%	1 %	3 %	6 %	11 %	13 %	15 %	16 %

The electricity storage systems create additional flexibility options for load smoothing, which can be classified as storage output (measured in GW) and storage capacity (measured in TWh).

The average annual electricity demand of a four-person household in a single-family house amounts to 5 MWh. In order to meet this demand using PV self-consumption, a 5 kW system is needed. A suitable storage capacity that provides sufficient electricity for the night is 3.75 kWh. Inverters currently have an efficiency of 96%; the storage itself has an efficiency of 92%. The discharge depth of the battery storage system is 90%.

These assumptions were made analogously to the approved scenario framework of the German Grid Development Plan for Electricity 2030, Version 2017 (BNetzA 2016). The assumptions are conservative to the extent that no significant technological progress is assumed between 2020 and 2050.

Table 7-1 also shows the share of PV electricity generation (including self-consumption via battery storage) in the total electricity generation based on renewable energies before the remainder is entered in the market modelling. In the *energy transition reference* scenario the share increases from 1% in 2020 to 8% in 2050; in the *solar focus* scenario it increases from 1% in 2020 to 16% in 2050 due to the higher expansion dynamics of storage and to the higher PV capacity.

7.2.3 Modelling of PV self-consumption

In the modelling of PV self-consumption, the regional PV patterns as well as the regional demand curves of the PV systems equipped with storage systems and of the associated households are used. In order to minimize grid-based electricity purchases, the electricity generated from PV is used immediately whenever possible. If this is not possible, the electricity can be stored up to the existing storage capacity or fed into the electricity grid. Using the storage capacity is advantageous since it avoids future electricity purchases from the grid. The value of the latter is minimized in the optimization process.

7.2.4 Modelling results for PV self-consumption

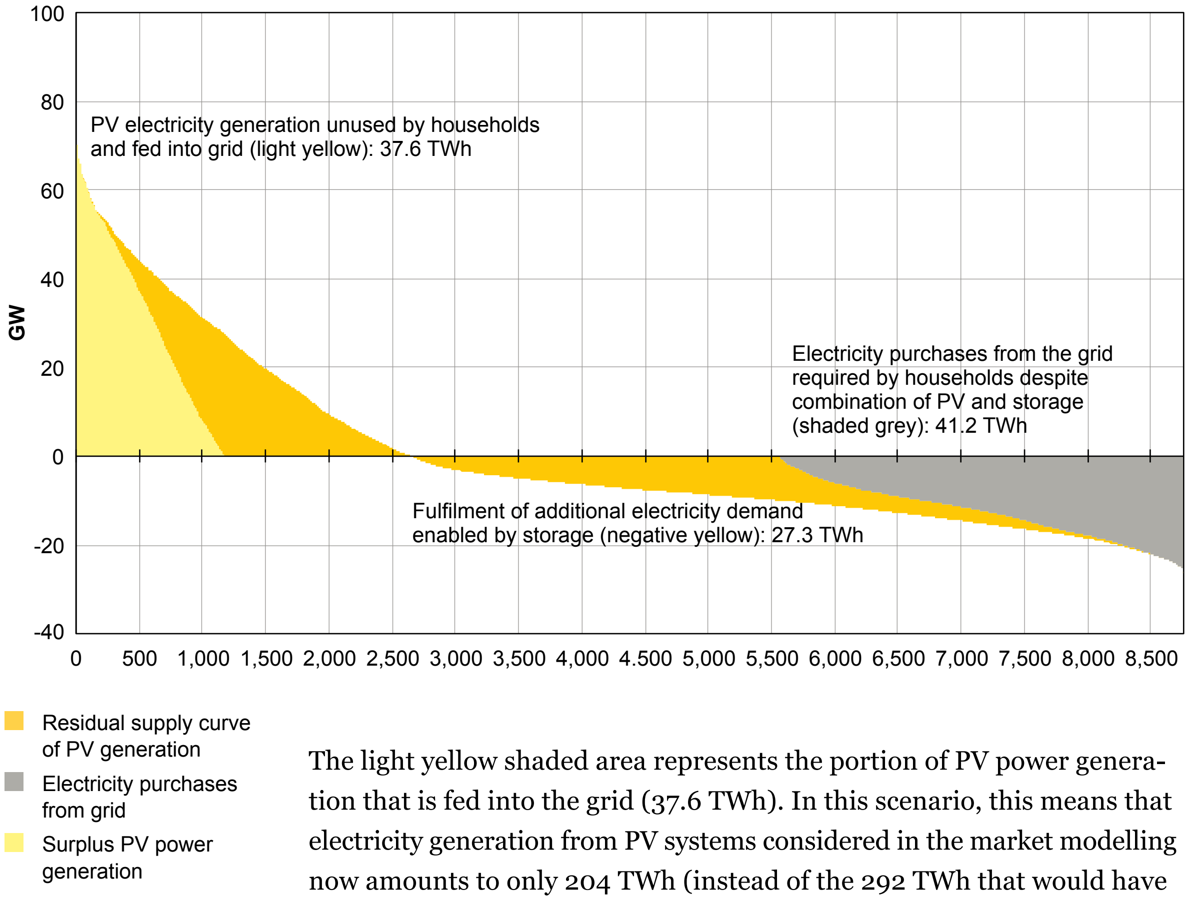
Since the parameters of PV storage systems and the assumptions about typical household characteristics are kept constant, the share of household demand that can be met via PV self-consumption is a constant value across all scenarios: 67% of household demand assigned to PV storage systems can be met using PV electricity generation; 22% of this household demand can be met by using battery storage.

The absolute values vary between the scenarios. In the *solar focus* scenario in 2050, 126 TWh of the overall 292 TWh are generated by roof-mounted PV systems equipped with storage ("PV-SC electricity generation"). Almost half of PV-SC electricity generation (58 TWh) can be used directly.

Figure 7-2 shows the results of further optimization of PV self-consumption using the example of the *solar focus* scenario in 2050. The yellow area shows the residual of the remaining PV power generation (i.e. the difference between hourly demand and hourly production) arranged in descending order. The value is positive when PV power generation exceeds household demand and negative when PV power generation of the specific hour is not sufficient to meet household demand. The latter is the case in 70% of hours of the year. The yellow in the positive area represents the share of PV electricity generation that can be temporarily stored (30.9 TWh). This stored electricity is then used to meet the previously unmet household demand. This is possible for up to 27.3 TWh in the *solar focus* scenario. With the exception of storage losses, the positive and negative yellow areas therefore correspond.

Figure 7-2: **Contribution of storage to optimizing PV self-consumption in *solar focus* scenario, 2050**

Source: Öko-Institut



The light yellow shaded area represents the portion of PV power generation that is fed into the grid (37.6 TWh). In this scenario, this means that electricity generation from PV systems considered in the market modelling now amounts to only 204 TWh (instead of the 292 TWh that would have been generated in the fully centrally coordinated market without the upstream optimization of PV self-consumption).

85 TWh of German electricity demand is already covered by the upstream optimization of PV self-consumption and is no longer relevant for the market modelling. The upstream optimization of PV self-consumption thus leads to an average reduction of 61.6% of household demand (originally 138 TWh) to be met via the central electricity market.

In order to fully meet the electricity demand of households with PV battery storage, 41.2 TWh would have to be drawn from the grid. In Figure 7-2 the grey shaded area shows this unmet demand.

7.2.5 Conclusion

The optimization of PV self-consumption has the effect of balancing demand and the supply of renewable energies to a substantially greater extent without using the transmission grid than would be the case without upstream optimization of PV self-consumption. In order to analyze to what extent the temporarily stored and locally used 30 TWh reduce pressure on the extra-high voltage grid through upstream optimization of PV self-consumption, a sensitivity calculation for 2050 was conducted for the *solar focus* scenario. In this sensitivity calculation, the effects of PV self-consumption systems on grid expansion needs were examined (see chapter 7.4.7.7).

7.3 Modelling results for overall electricity market

7.3.1 Electricity generation

The graphs below show electricity supply in Germany in the *energy transition reference* scenario and the *solar focus* scenario. In order to keep within the remaining emissions budget of a maximum of 4 Gt CO_2 emissions for the electricity sector, all coal-fired power plants in operation for more than 30 years are shut down from 2019 onwards. In addition, coal-fired power plants are subject to CO_2-optimized operation from their 21st operation year onwards, as discussed in chapter 4.1. In both scenarios this leads to a substantial reduction in electricity generation from coal-fired power plants from 2019 onwards. At the same time, there is a temporary increase in electricity generation from natural gas-fired power plants. At the end of 2035, electricity generation from coal-fired power plants is completely stopped, with the result that in 2040 only renewable energies, natural gas and other fossil fuels such as special gases and fossil waste are used. According to Germany's current regulations, electricity generation from nuclear energy is to be phased out by the end of 2022 at the latest.

With regard to Germany's electricity import and export balance with neighbouring countries, most scenario years show net electricity exports. There are two exceptions: the years 2020 and 2040 have low net imports of a maximum of 5 TWh and 17 TWh respectively. Low net imports come about in 2020 because power plants in European neighbouring countries are more frequently included in the European merit order due to the shutdown of the old coal-fired power plants in Germany. In the vast majority of hours there are net imports even though power plant capacity would still be available in Germany. These net imports are primarily market-driven. In 2040, a strong increase in Germany's electricity demand leads to net imports due to the increase in sector coupling. In the years following 2040, the further expansion of renewable energies balances this increase and even proceeds to overcompensate it.

By definition, the share of renewable energies rapidly increases in both scenarios, with the result that by 2030 renewable energies account for more than 80% of Germany's net electricity supply. After 2030 the rapid expansion of electricity generation from renewable energies continues, albeit in the context of a substantial increase in electricity consumption (see chapter 4.3).

In the *energy transition reference* scenario, onshore wind energy brings about by far the largest share of electricity generation. In the *solar focus* scenario, solar energy generates the largest share of electricity from 2035 onwards.

Figure 7-3: **Electricity generation in Germany in the *energy transition reference* scenario, 2015–2050** Source: Öko-Institut

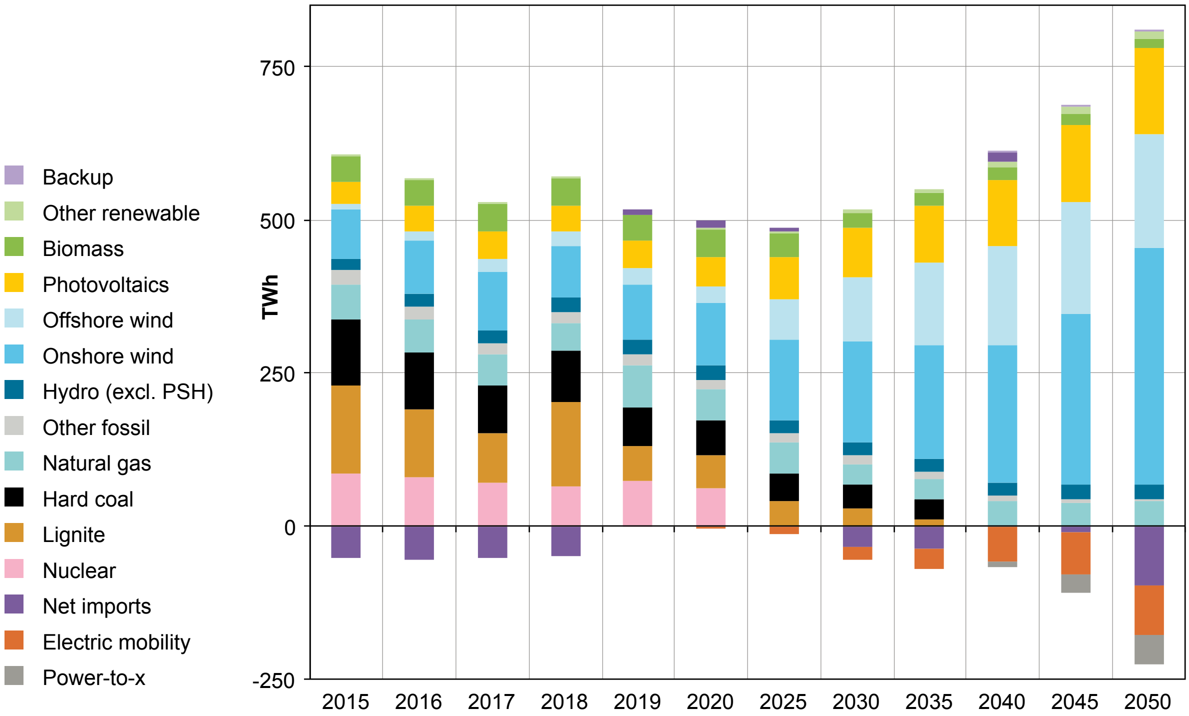


Figure 7-4: **Electricity generation in Germany in the *solar focus* scenario, 2015–2050** Source: Öko-Institut

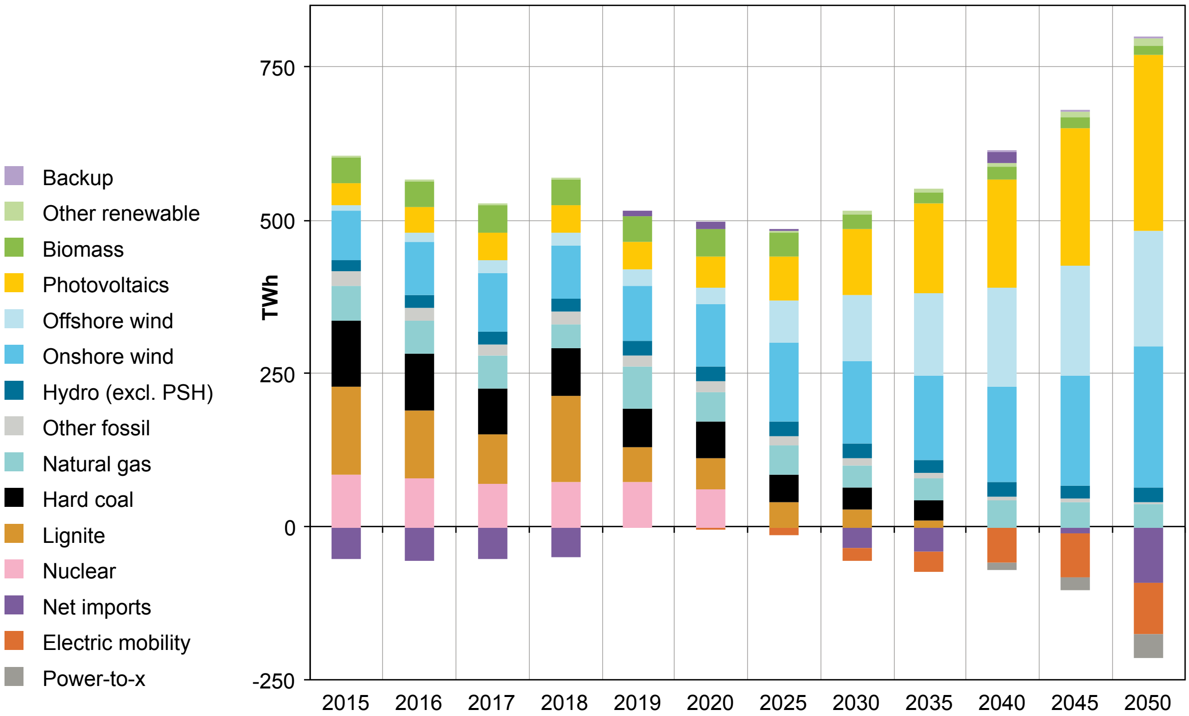


Figure 7-5: **Electricity generation from wind and solar power plants in Germany, 2020–2050**

Source: Öko-Institut

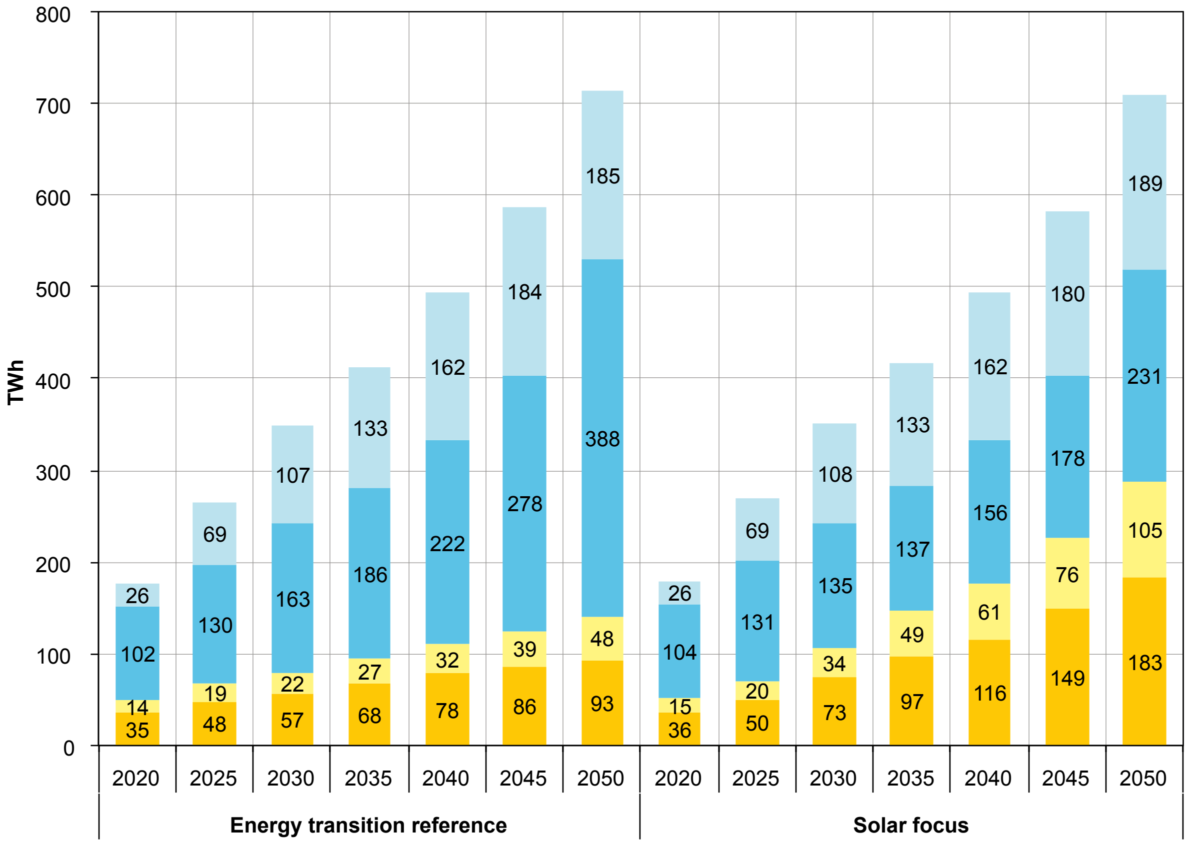


Figure 7-5 juxtaposes renewable electricity generation in the two scenarios and shows the shares of roof- and ground-mounted systems in electricity generation from solar energy. Although the installed capacity of offshore wind turbines is the same in both scenarios, the electricity generation from this source differs slightly from 2045 onwards as there are unused surpluses of renewable electricity in both scenarios, as Table 7-2 shows. Overall, wind and solar power plants generate the same quantity of electricity in both scenarios.

The market-related renewable feed-in peaks that cannot be used for load coverage in the model despite flexibility options range between zero and a few terawatt hours in most years. Only in 2050 do the market-related surplus renewable feed-in peaks amount to approx. 30 TWh (*energy transition reference*) and approx. 40 TWh (*solar focus*). With a view to the high electricity generation from fluctuating renewable energy sources in 2050, these shares amount to 4% and 5% respectively.

Table 7-2: **Market-related surplus of renewable electricity generation**

Source: Öko-Institut

	2020	2025	2030	2035	2040	2045	2050
	TWh						
Energy transition reference	0	0	1	3	0	5	33
Solar focus	0	0	1	3	1	10	39

In the modelling the different feed-in characteristics of wind and solar energy lead to very small shifts in the other energy sources, the import-export balance and flexible consumption. The latter includes electric mobility (which is mapped in the model with charging behavior that is market-related and steered) and systems for the production of electricity-based synthetic fuels (power-to-x).

Figure 7-6: **Difference of supply and demand of flexible consumption between the *solar focus* and the *energy transition reference* scenario (w/o onshore wind and PV)**

Source: Öko-Institut

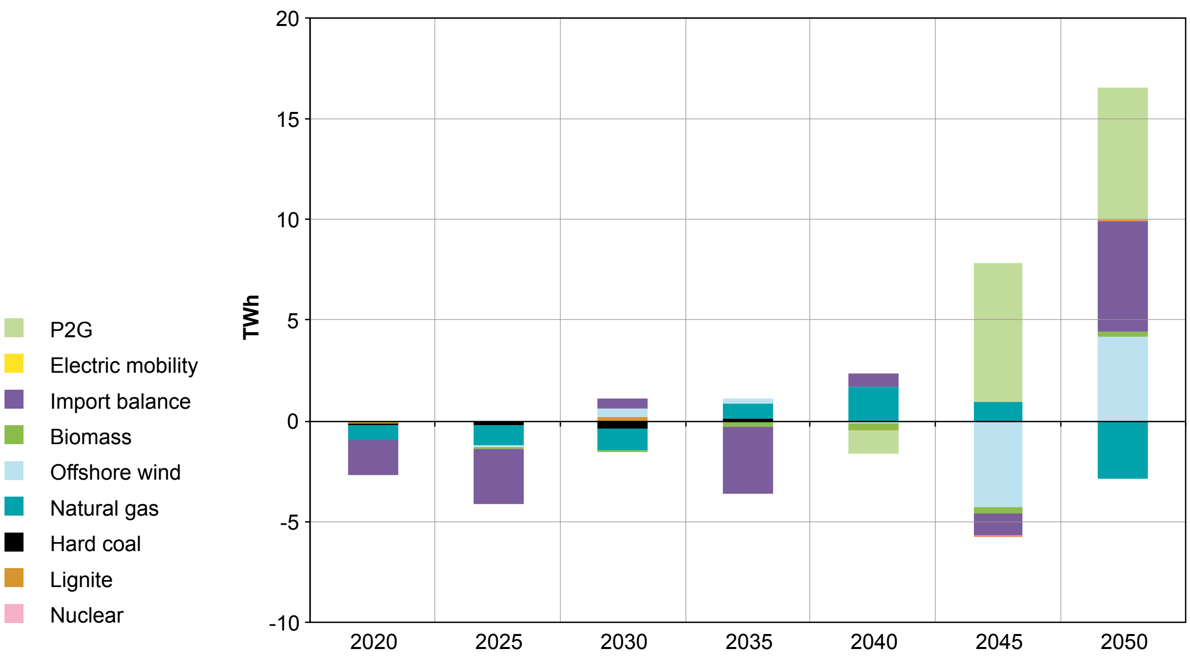


Figure 7-6 shows the differences between the scenarios in this respect. In 2045 and 2050, the *solar focus* scenario shows a slightly higher electricity consumption of systems for the production of electricity-based synthetic fuels. The other parameters of the scenarios differ by only a few terawatt hours.

7.3.2 CO_2 emissions

The following graphs show the annual CO_2 emissions of fossil-fired power plants in both scenarios. CO_2 emissions decrease from approx. 350–300 million t in 2015-2018 to approx. 170 million t in 2020, approx. 140 million t in 2025, approx. 110 million t in 2030, and approx. 80 million t in 2035. From 2040 to 2050, annual CO_2 emissions are below 50 million t.

The shares of the different fuels in total CO_2 emissions shift significantly between 2015 and 2050. While CO_2 emissions from lignite and hard coal power generation still account for approx. 80% of the total CO_2 emissions from electricity generation in 2015, the share of CO_2 emissions from coal decreases to only approx. 60% in 2019 and 2020 and to approx. 50% in 2035. From 2040, the only fossil CO_2 emissions come from natural gas and the other fossil fuels (fossil waste, special gases).

The diagrams also show (as red numbers) the cumulative CO_2 emissions over the entire period, which amount to approx. 4.1 Gt in both scenarios. That the German electricity sector more or less stays within its CO_2 emission budget is mainly due to the rapid and substantial reduction in CO_2 emissions as early as 2019 based on measures for accelerating the phase-out of coal-fired electricity generation.

With regard to emission reductions in the electricity sector, it should be noted – alongside the large contribution currently made by electricity generation to total greenhouse gas emissions in Germany – that rapid decarbonization of the electricity sector is also a key parameter for rapid emission reductions in the other sectors (electric mobility, electrification of the heat sector in its different segments).

Figure 7-7: **CO_2 emissions from fossil-fired power plants in *energy transition reference* scenario, 2015–2050**

Source: Öko-Institut

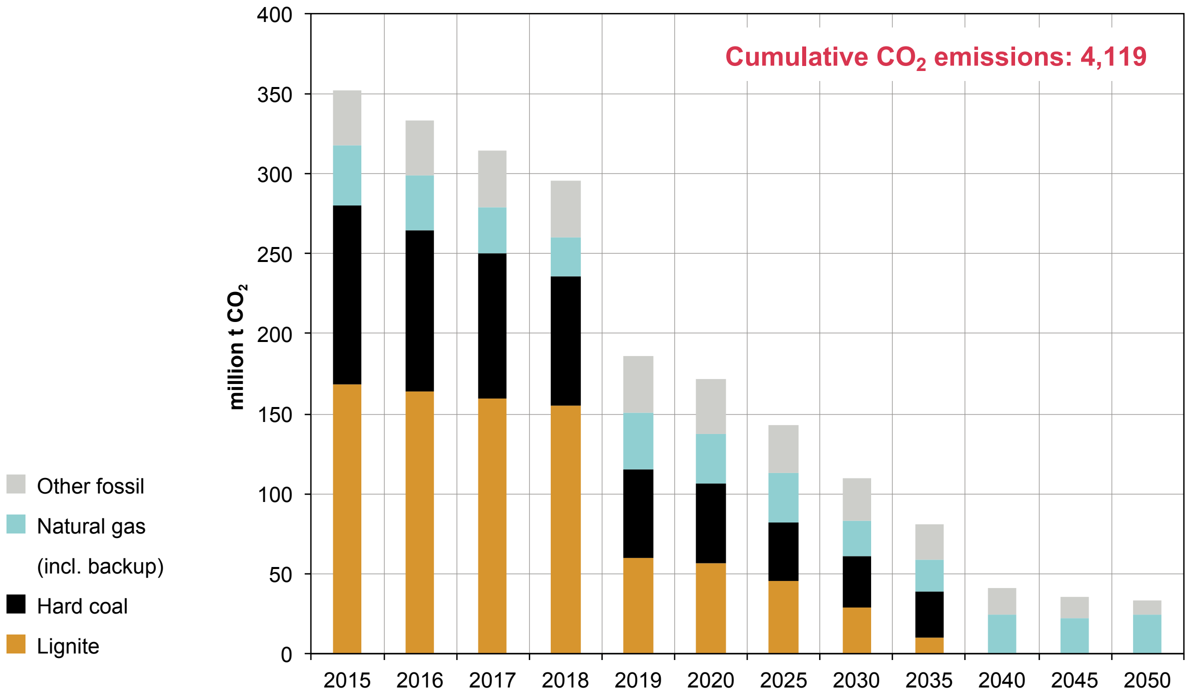
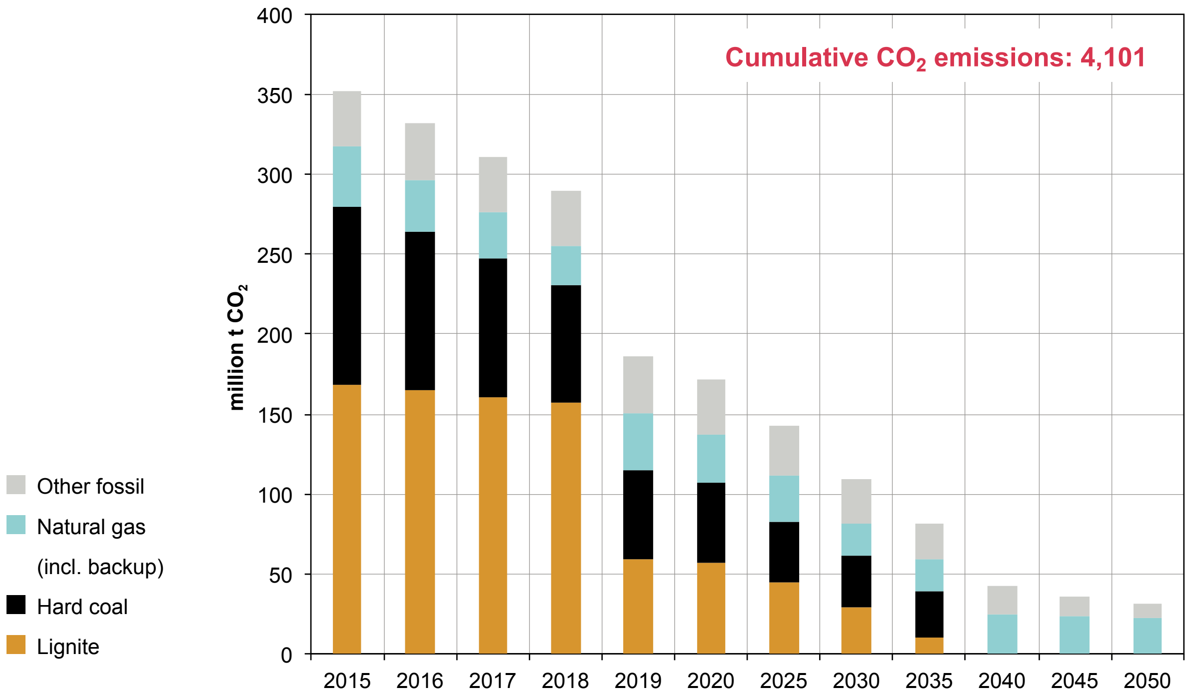


Figure 7-8: **CO_2 emissions from fossil-fired power plants in *solar focus* scenario, 2015–2050**

Source: Öko-Institut



7.4 Grid expansion decisions and infrastructure costs

7.4.1 Preliminary remarks

The huge expansion of electricity generation based on renewable energies can necessitate the expansion and redesign of grid infrastructures. In particular, deciding on a certain expansion path and technology mix for renewable energies can have an impact on grid expansion decisions.

In order to make statements on the grid expansion needs of the different scenarios, a load flow simulation and an ex-post estimation of grid expansion needs were added to the electricity market modelling. The procedure used for this is explained in the following sections.

7.4.2 Load flow simulation: simplifying the load flow equation

In a load flow simulation, the power flow of the different transmission lines is calculated for both active and reactive power using the non-linear load flow equations listed in Annex 5. From a modelling perspective, it is helpful to simplify the load flow equation to bring about a linear correlation between feed-in at the nodes and the resulting load flow. In this way the load flow can be estimated with sufficient accuracy. The load flow equation can be reduced to a linear correlation based on three main assumptions described in Annex 5. These assumptions ensure that no line losses occur and that only active power is transmitted. This approach is legitimized by, for example, a study by Bucksteeg (2012), which conducted a load flow simulation in the German extra-high voltage grid using both approaches and assessed the difference to be "sufficiently small".[23]

23 Taking into account the rules established by Purchala for error estimation of the DC load flow simulation, the calculated load flow for >95% of the German extra-high voltage lines should deviate by a maximum of 5% from the correctly calculated load flow (Purchala et al. 2005).

7.4.3 Grid topology

The resulting load flow is dependent on the grid topology. The grid topology was not varied between scenarios and reference years. As explained in chapter 4.5, the target grid of the second draft of Germany's Grid Development Plan for Electricity in 2025 was taken as a basis (50Hertz Transmission GmbH et al. 2016).

The load flow simulation provides a node-specific map of the German extra-high voltage grid. The grid topology is composed of 557 high-voltage nodes, 780 alternating current (AC) lines, 5 direct current (DC) lines and 35 foreign transmission lines. The power grid on which the load flow simulation is based is shown in chapter 4.5, Figure 4-7. The grid topology is considered to be a static grid.

7.4.4 Grid expansion options

It is not the aim of this study to undertake a detailed calculation of grid expansion needs. The grid overloads are used exclusively to estimate the scope of the scenario-based grid expansion needs and to determine how these needs differ between the two scenarios.

For the ex-post evaluation of grid expansion needs, it was assumed that all existing transmission lines of the target grid of the Grid Development Plan B 2025 can, in principle, be expanded. The option of installing new power lines beyond this, i.e. with completely new routes, was not considered.

7.4.5 Regionalization of input data and modelling results

In order to conduct a load flow simulation, the input data of the modelling and the results of the market simulation have to be available in node-specific resolution.

The input data was regionalized in the data processing phase of the project (see chapters 4 and 6), so that the results of the market simulation can, as far as possible, be classified regionally. The following assumptions were nonetheless necessary:

- the market-related RES curtailment was regionalized in proportion to the availability of renewable energies;
- the charging and storage patterns of electric vehicles produced by the model were regionalized in proportion to the number of vehicles;
- the use of power-to-gas was regionalized according to the availability of onshore wind feed-in; and
- the market-related use of demand side management is based on the existing availability of demand flexibility.

With the help of these assumptions, it was possible to assign the centrally determined electricity market results of the modelling to the different grid nodes as electricity generation or as electricity demand.

7.4.6 Ex-post estimation of grid expansion needs

The scenario-related grid expansion needs are estimated based on the utilization rates resulting from the load flow simulation. As soon as a utilization rate significantly exceeds its thermal load limit, its transmission capacity is increased by the addition of a further circuit. Such an expansion comes about when more than 120% of the transmission line capacity is used.

The expansion brought about by a new circuit is realised in the form of a standard AC line (380 kV) with a transmission capacity of 1,600 MW and an average line resistance. Analogous to the Grid Development Plan for Electricity 2025 (NEP 2025), the investment needs are assumed to be € 0.2 million per kilometre of transmission line (see the background material on cost estimates for the NEP 2025[24]).

For 2020 and 2025, both scenarios assume that no grid expansion needs arise beyond those in the NEP 2025. Accordingly, the grid expansion needs are estimated only from 2030 onwards.

The calculated grid expansion needs are set in relation to the grid expansion needs of the NEP 2025 and are provided as investment volumes.

24 https://www.netzentwicklungsplan.de/de/kostenschaetzungen-zu-kapitel-42-0

7.4.6.1 Boundaries of ex-post estimations

The methodology employed in this study to estimate future grid expansion needs should be used for indicative purposes only. The following uncertainties should be noted:

If a grid expansion option is implemented, only the overload on the power line concerned is reduced. In reality, however, the grid expansion can have the effect of relieving pressure on the grid, an effect which covers several power supply lines. In this respect, the grid expansion needs are overestimated.

The option of constructing new power lines along new routes basically leads to a reduction in grid expansion needs. Since new routes are not considered in this indicative approach, grid expansion needs tend to be overestimated.

In one scenario, the grid expansion needs for each reference year are calculated based on the second draft of the Grid Development Plan for Electricity (NEP B 2025). The grid expansion measures specified for the scenario year of 2030 have, therefore, not yet been included in the grid for the 2035 scenario year and have to be re-calculated. Since it has not been verified whether the grid expansion measures identified for 2035 are the same as for 2030, grid expansion needs may be underestimated.

The methodology for estimating grid expansion needs does not take into account that the electricity grid should remain free of bottlenecks even in the event of the failure of an important grid element ("(n-1)- safety"). Many models incorporate the (n-1) criterion by deducting a safety margin of 30% from the thermal limits of the transmission line. Since the present study requires only an estimate to be made, the (n-1) criterion was not used. This leads to an underestimation of grid expansion needs.

It can be concluded, then, that the method chosen for estimating grid expansion needs has the effect of both underestimating and overestimating these future needs. This brings about a partial balancing of the effects. Other analyses currently being conducted by Öko-Institut, however, show that the grid expansion needs resulting from applying the safety margin (n-1) have a relevant effect. It is assumed on this basis, then, that the chosen methodology tends to underestimate the actual grid expansion needs, but provides an acceptable idea of their order of magnitude. This is especially the case when it is considered that new approaches to grid operation may reduce grid expansion needs in future (within certain limits) (see chapter 7.4.7.3).

The chosen approach produces robust estimates of future investment needs for transmission grid infrastructures. It also enables corresponding comparisons of the two scenarios and the identification of regions that are problematic in future from a grid planning perspective.

7.4.7 Results

Up to 2025 it is assumed irrespective of the scenario that the redesign of the transmission grids in the NEP 2025 is sufficient to incorporate the generation of the renewable power plant fleet. Figure 7-9 shows the calculated investment volumes needed for grid expansion from 2030 onwards.

Up to 2030, there is a slight additional need for grid expansion independent of the scenarios, which necessitates an additional investment volume amounting to approx. 10% of the Grid Development Plan (NEP).

From 2035 onwards, the calculated grid expansion needs are different for the two scenarios. In the *energy transition reference* scenario, an additional investment volume of approx. 30% of the NEP is needed by 2035. In the *solar focus* scenario, the investment needs for the transmission grid infrastructure are lower, at approx. 23% of the NEP.

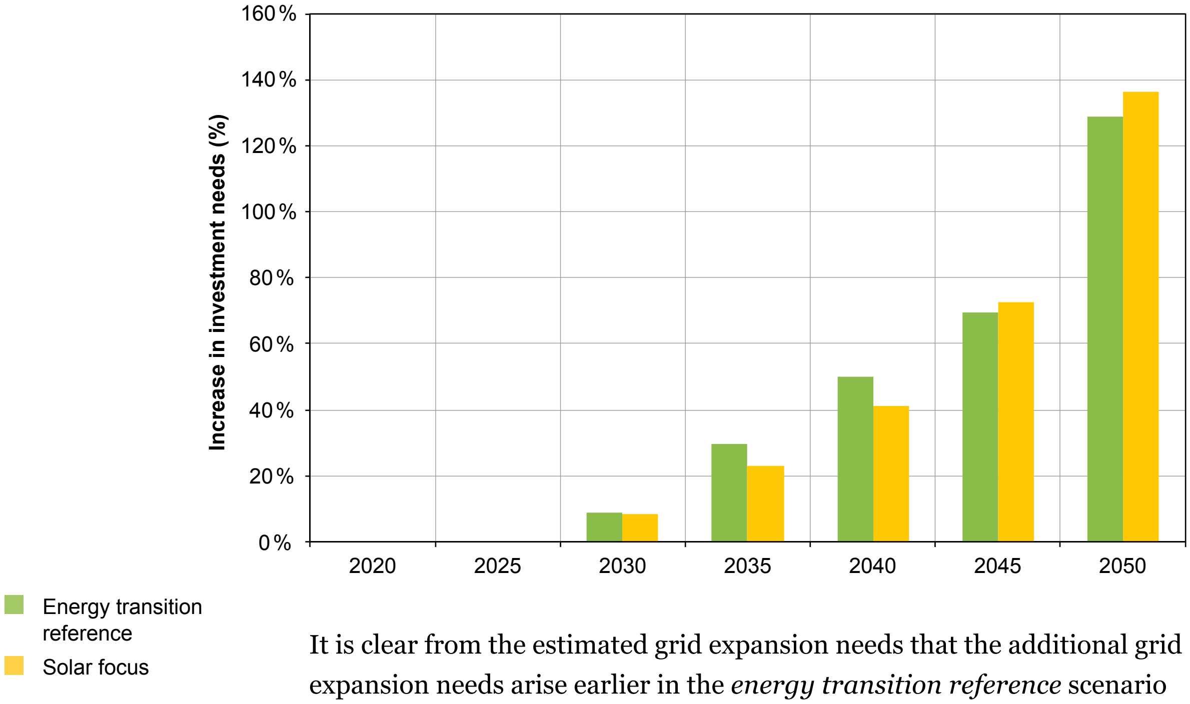
This trend continues up to 2040. Here, too, the grid expansion needs in the *energy transition reference* scenario are substantially higher than in *solar focus* scenario, with an investment volume of approx. 50% of the NEP compared to approx. 41% of the NEP.

From 2040, however, additional grid expansion needs increase more quickly in the *solar focus* scenario. The *energy transition reference* and the *solar focus* scenarios converge up to 2045 as far as the absolute grid expansion needs are concerned: in both scenarios, the investment volumes constitute approx. 70% of the NEP.

The continued expansion of renewable energies results in substantial additional grid overloads in both scenarios by 2050. Again, the *solar focus* scenario is more strongly affected by this than the *energy transition reference* scenario: by 2050, the additional grid investments total approx. 1.3 (*energy transition reference* scenario) and 1.4 (*solar focus* scenario) times the investment volumes foreseen in the NEP.

Figure 7-9: **Investment needs of different scenarios in relation to those of Grid Development Plan B2 2025**

Source: Öko-Institut



It is clear from the estimated grid expansion needs that the additional grid expansion needs arise earlier in the *energy transition reference* scenario than in the *solar focus* scenario. In the long run, however, the absolute value of the grid expansion needs balances out as far as possible: in the *solar focus* scenario, the grid expansion needs are somewhat higher than in the *energy transition reference* scenario.

As the detailed results in the following chapters demonstrate, the actual decisions about grid expansion differ in the two scenarios: while in the *energy transition reference* scenario greater grid expansion needs are structurally visible in a north-south direction; in the *solar focus* scenario these needs predominantly arise on the east-west and south-centre axes.

7.4.7.1 Basis: Reference scenario of Grid Development Plan B2 2025

The target grid developed for 2025 in the B2 reference scenario of the NEP 2025 (NEP B2 2025) is assessed by transmission system operators as sufficiently free of bottlenecks (50Hertz Transmission GmbH et al. 2016). If this scenario of the NEP is recalculated, it can be assumed that here, too, maximum capacity utilizations of power lines arise that exceed their thermal limits. However, these overloads are evaluated as so uncritical that the bottleneck in grid operation can be rectified. These rectifying measures include dynamic grid control, redispatch or feed-in management.

Nevertheless, it can be assumed that the results of the simplified load flow simulation used in this study differ from those of an AC load flow simulation due to the approach and the simplified grid topology used[25]. In order to adjust the results to account for the model-related overestimation of grid expansion needs, the market result is also calculated for the scenario of the NEP B2 2025 and compared with that of the transmission grid operators. If these two results correspond, the model is regarded as calibrated. Subsequently, the simplified load flow simulation is conducted and the resulting grid expansion needs are determined.

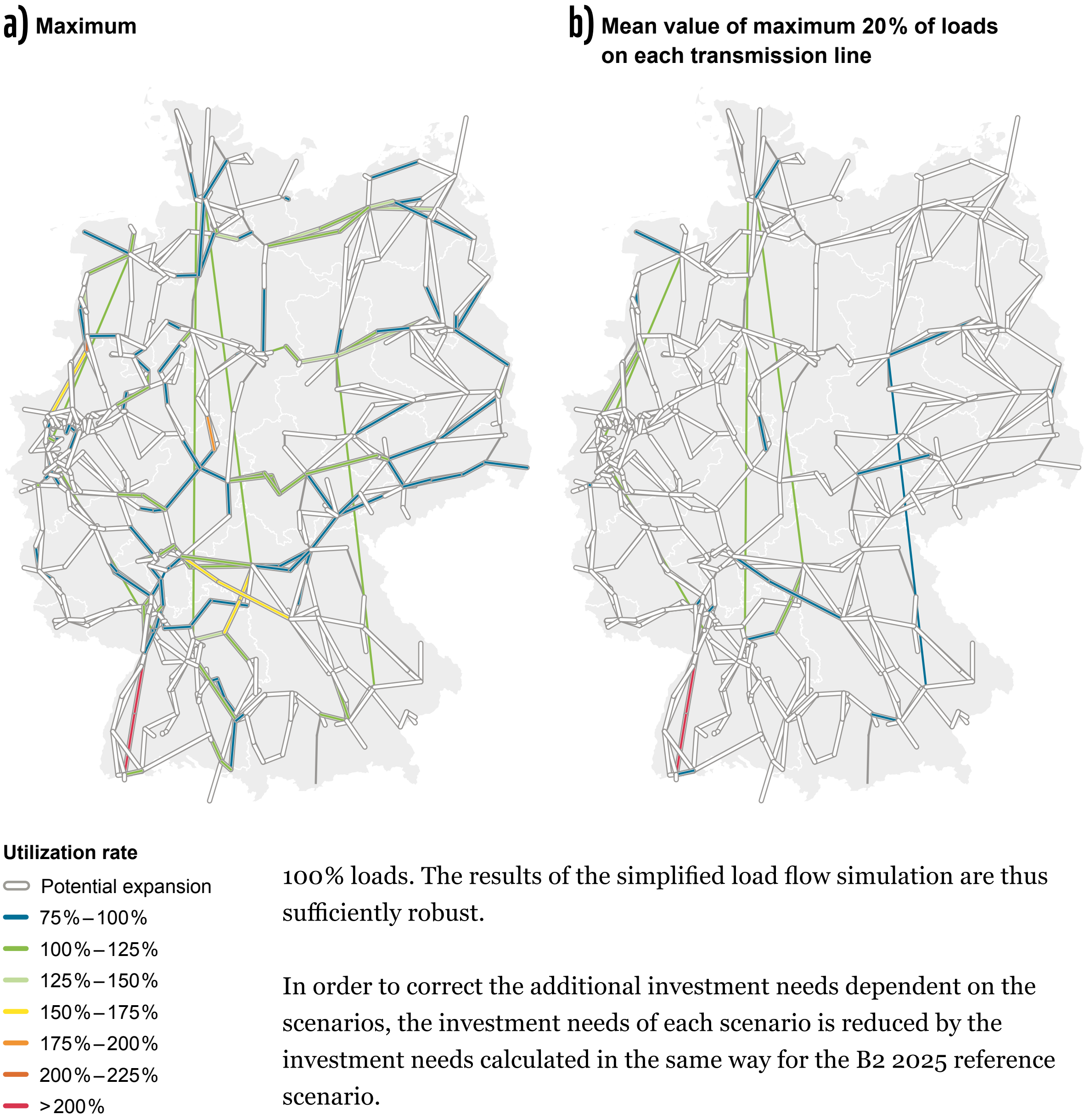
Figure 7-10a shows the maximum utilizations of transmission lines in the NEP scenario B2 2025 (calculated using the simplified load flow simulation), which arise in one hour of the scenario year under consideration. The transmission lines on which the maximum utilization is >70% of the thermal limit are highlighted. In the NEP B2 2025 reference scenario, the mean value of the overloaded transmission lines is 134%. The Rhine line in Baden-Württemberg is the most overloaded one on the grid, with a maximum load of 373%. In this case it is assumed that there is an error in the grid topology.

Figure 7-10b shows the mean value of the 20% of the hours in the scenario year in which the transmission line is very heavily loaded (referred to as "mean max 20"). If a line is no longer highlighted in this diagram, it means that the overload occurred for only a few hours and that a grid expansion is not necessary here. With regard to the NEP reference scenario, it becomes clear that – apart from the Rhine line – only the DC corridors have approx.

25 The data set of the Federal Network Agency (BNetzA), which can be requested under §12f, was used as the grid topology. The grid topology used by the TSOs is more detailed; it includes, for example, the 110 kV grid.

Figure 7-10: **Maximum utilization rates in reference scenario of Grid Development Plan B 2025**

Source: Öko-Institut

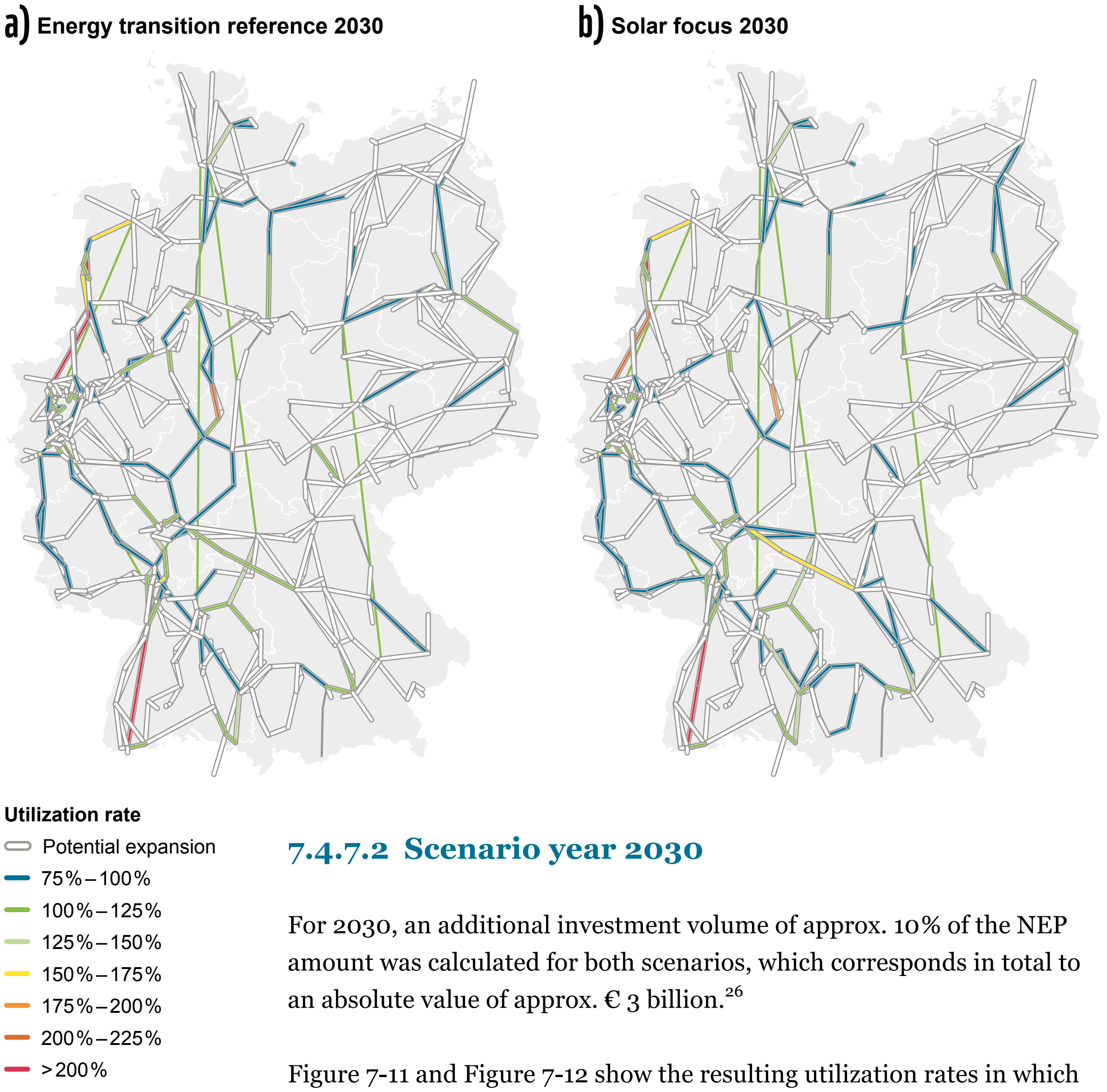


100% loads. The results of the simplified load flow simulation are thus sufficiently robust.

In order to correct the additional investment needs dependent on the scenarios, the investment needs of each scenario is reduced by the investment needs calculated in the same way for the B2 2025 reference scenario.

Figure 7-11: **Maximum utilization rates in the scenarios, 2030**

Source: Öko-Institut



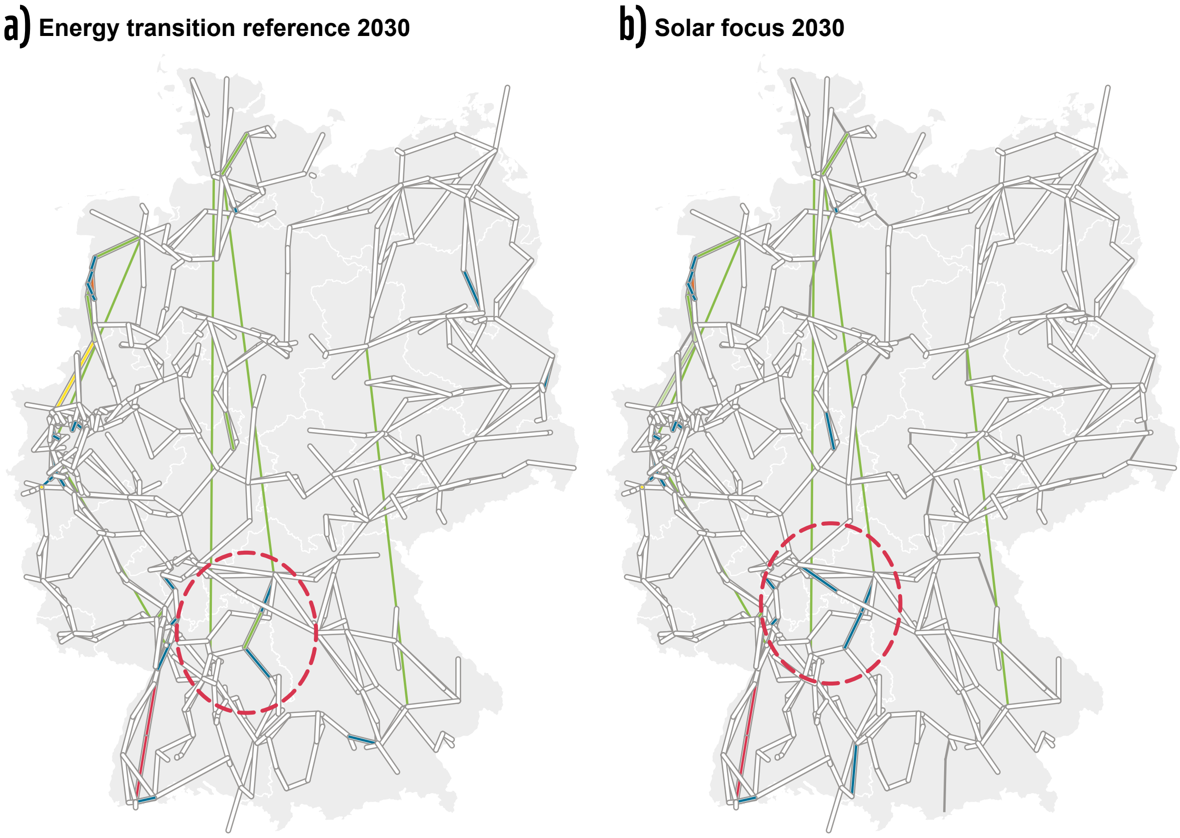
7.4.7.2 Scenario year 2030

For 2030, an additional investment volume of approx. 10% of the NEP amount was calculated for both scenarios, which corresponds in total to an absolute value of approx. € 3 billion.[26]

Figure 7-11 and Figure 7-12 show the resulting utilization rates in which the maximum loads and the "mean max 20" of the two scenarios are highlighted. A large portion of grid congestion occurs in identical places and at similar levels in the scenarios. 84% of the grid expansion needs identified in the *energy transition reference* scenario are also included in the *solar focus* scenario. 79% of the grid expansion needs in the latter scenario involve the same routes as in the *energy transition reference* scenario. The mean value of all maximum overloads is 147% in the *energy transition reference* scenario, and 151% in the *solar focus* scenario.

26 It should be noted that these investment costs are for very long-lived infrastructures, which depreciate over long periods of time. Broken down to the year, the annuity values for the system costs are lower by a factor of 17, see chapter 7.5.

Figure 7-12: **Maximum utilization rates of "mean max 20" in the scenarios, 2030** Source: Öko-Institut



Utilization rate

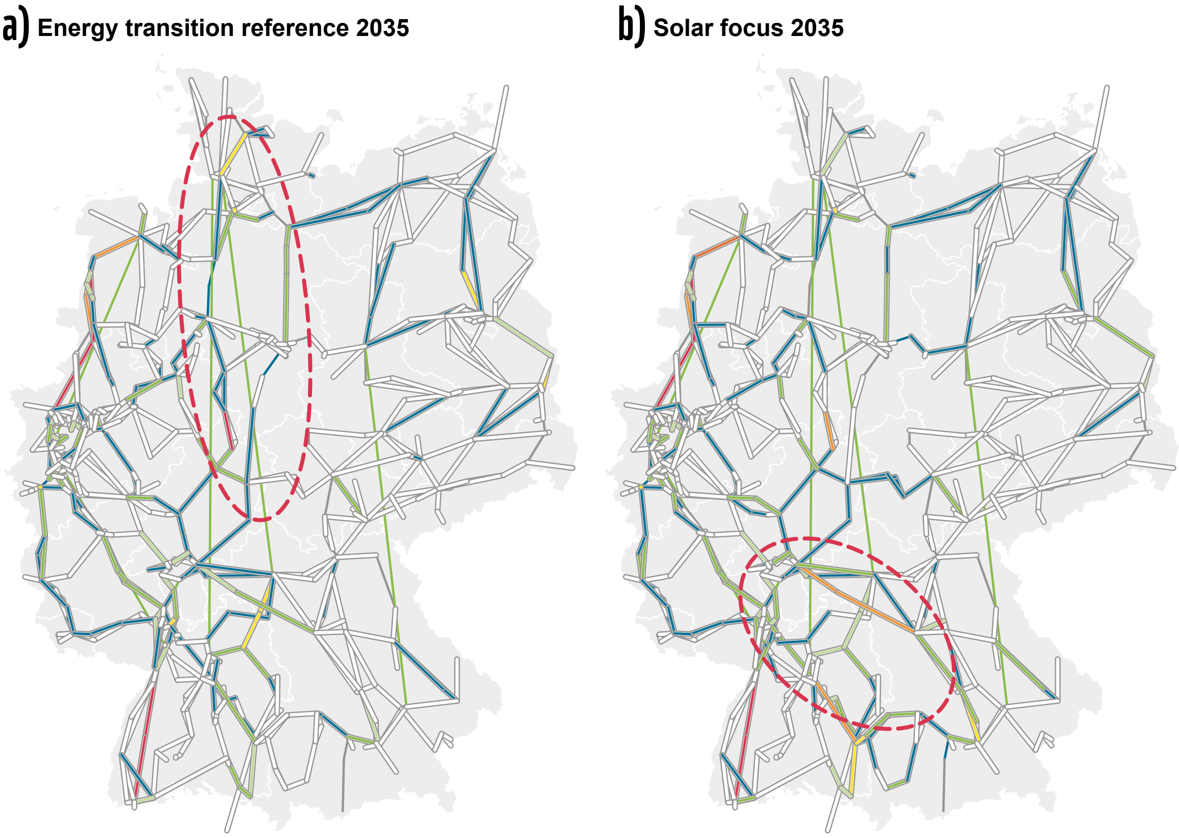
- Potential expansion
- 75 % – 100 %
- 100 % – 125 %
- 125 % – 150 %
- 150 % – 175 %
- 175 % – 200 %
- 200 % – 225 %
- > 200 %

In the "mean max 20", slightly more bottlenecks remain in the *energy transition reference* scenario, which means that the new overloads in this scenario also occur more frequently at the same location. A possible cause for this grid expansion need arising independently of the scenarios is the identical increase in offshore wind power in both scenarios: between 2025 and 2030, the installed capacity of offshore wind power plants is increased from 18 GW to 27 GW.

The calculated grid expansion needs that go beyond the NEP, however, still show no dependency on the expansion path of renewable energies.

Figure 7-13: **Maximum utilization rates in the scenarios, 2035**

Source: Öko-Institut

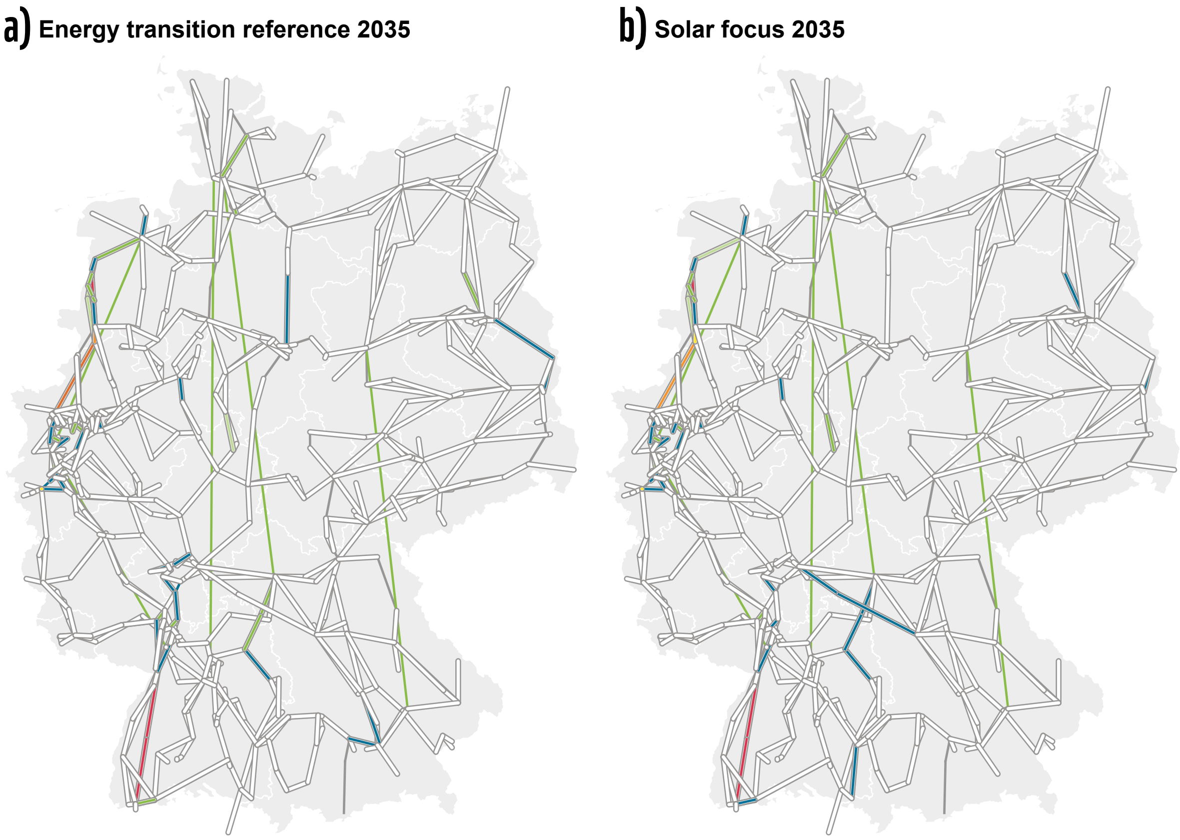


7.4.7.3 Scenario year 2035

Up to 2035, an additional investment volume of approx. 30% of the NEP was calculated for the *energy transition reference* scenario, which corresponds to approx. € 10.1 billion in total. In the *solar focus* scenario, the grid expansion needs that arise in addition to those of the NEP from 2025 onwards total € 7.9 billion, which corresponds to an additional investment volume of approx. 23% of the NEP.

Figure 7-13 and Figure 7-14 show the resulting utilization rates in which the maximum loads and the “mean max 20” of the two scenarios are highlighted. A large portion of the grid overloads continue to occur in identical places across all scenarios. 73% of the grid expansion measures identified in the *energy transition reference* scenario correspond to those in the *solar focus* scenario. The grid expansion needs of the latter occurs on a greater number of routes, although the absolute grid expansion needs are lower. 77% of the routes showing grid expansion needs correspond to those identified in the *energy transition reference* scenario.

Figure 7-14: **Maximum utilization rates of "mean max 20" in the scenarios, 2035** Source: Öko-Institut



Utilization rate

- Potential expansion
- 75 % – 100 %
- 100 % – 125 %
- 125 % – 150 %
- 150 % – 175 %
- 175 % – 200 %
- 200 % – 225 %
- > 200 %

In 2035 it becomes clear for the first time that structurally the grid expansion needs that deviate from each other in the *energy transition reference* scenario tend to be on the north-south axis, while in the *solar focus* scenario they tend to be on the south-west axis. Thus, the necessity and the effectiveness of an increasing share of the identified grid expansion needs depend on the chosen technology path and the corresponding regionalization of expansion in the use of renewable energies. These measures would have to be assessed as bad investments or "regret measures" if the transformation path were subsequently adjusted.

The mean value of all maximum utilization rates amounts to 149% in the *energy transition reference* scenario, and 144% in the *solar focus* scenario. For the "mean max 20", no relevant differences are identified between the scenarios up to 2035. This also indicates that the bottlenecks arising up to now could also be remedied by measures other than grid expansion.

In the medium term (up to 2030/35 at the latest) new technologies and, above all, the digitalization of transmission grid operation can bring about a substantially better grid utilization without any loss of system security. These include (Agora Energiewende 2018):

» comprehensive overhead line monitoring;

» increased automatization of system management;

» introduction of digital online help systems for a more timely evaluation of system security;

» increased measures for load flow control; and

» installation of high-temperature conductor cables.

Figure 7-15: **Maximum utilization rates in the scenarios, 2040**

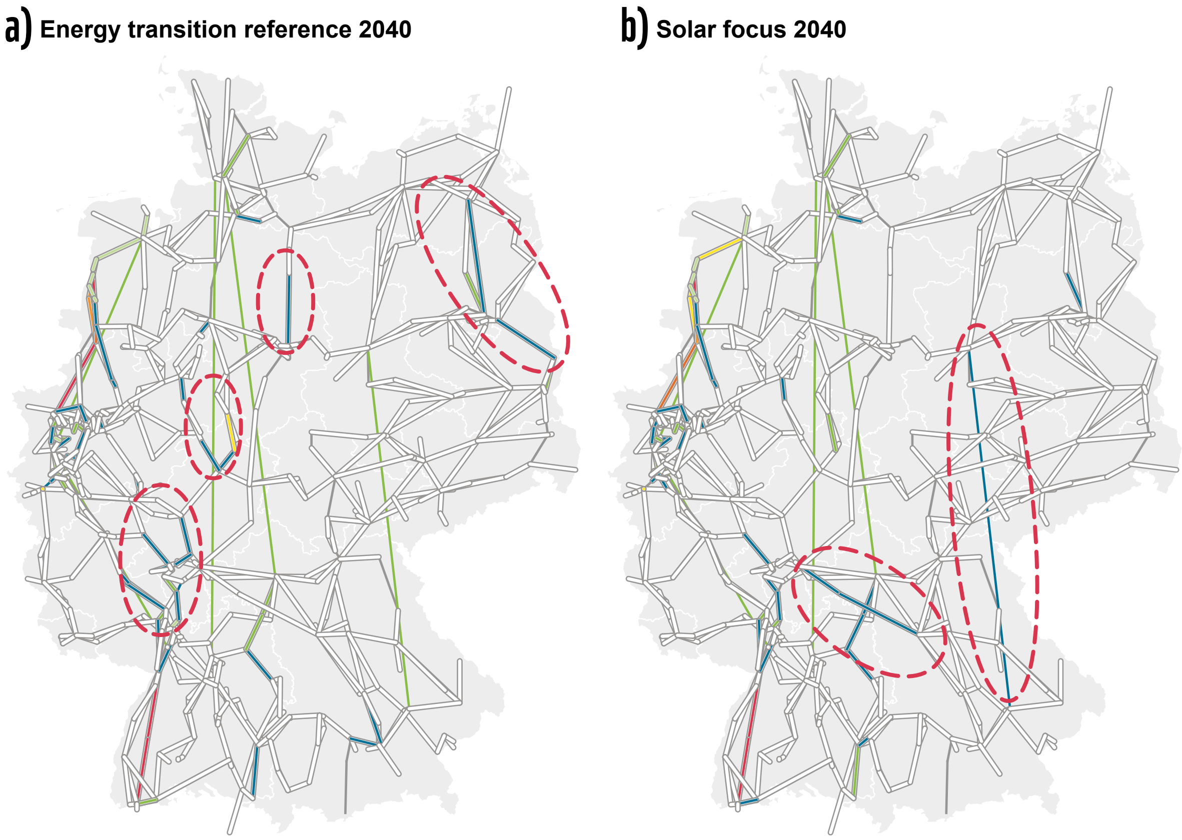
Source: Öko-Institut

7.4.7.4 Scenario year 2040

Up to 2040, an additional investment volume amounting to approx. 50% of the NEP was calculated for the *energy transition reference* scenario, which corresponds to a total of approx. € 17.0 billion. In the *solar focus* scenario, the grid expansion needs arising in addition to those of the NEP from 2025 onwards amount to € 14.0 billion, which corresponds to approx. 41% of the NEP. The grid expansion needs in the *solar focus* scenario are clearly below those that arise in a scenario that relies more strongly on onshore wind power.

Figure 7-15 and Figure 7-16 show the resulting utilization rates in which the maximum loads and the “mean max 20” of the two scenarios are highlighted. There continues to be a large overlap in the grid congestion in the two scenarios; this grid congestion continues to occur in identical places. 74% of grid expansion needs identified in the *energy transition reference* scenario also arise in the *solar focus* scenario. 83% of the routes on which maximum loads arise in the *solar focus* scenario also arise in the *energy transition reference* scenario.

Figure 7-16: **Maximum utilization rates of "mean max 20" in the scenarios, 2040** Source: Öko-Institut

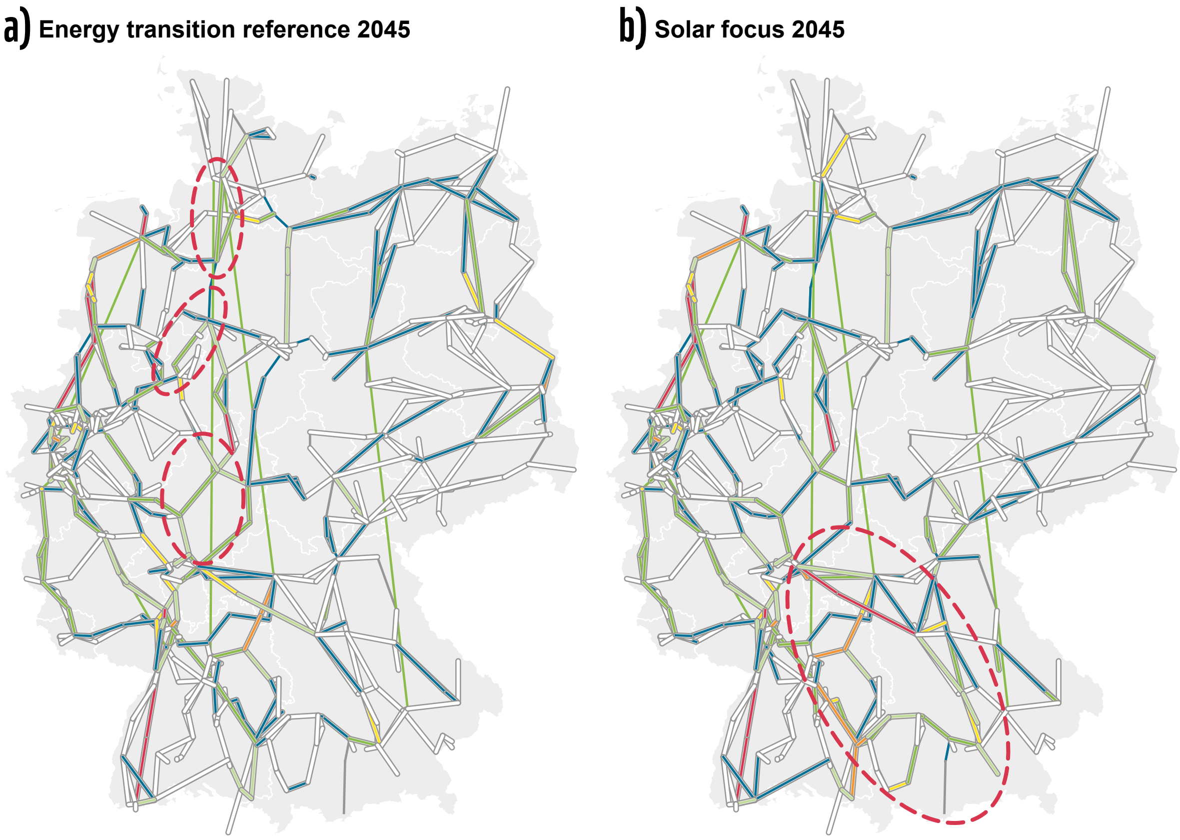


Although the mean value of all maximum overloads in both scenarios is still very comparable (*energy transition reference* scenario: 149%, *solar focus* scenario: 150%), regional differences in the degree of grid overload become clear. The north-south trend of the *energy transition reference* scenario, which was already apparent in 2035, becomes much more pronounced by 2040. In the *solar focus* scenario, significant bottlenecks arise on the south-west axis. This divergence in the bottlenecks still comes about when considering the 20% of hours in which the maximum utilization rates occur.

On the one hand, this shows that the bottlenecks should be rectified by grid expansion measures in 2040 at the latest. On the other hand, path dependencies come about at this time at the latest: depending on which technology mix is used in the expansion of renewable energies and how this expansion is regionalized, the grid expansion needs have regional differences. Since the implementation time frame of a grid expansion project is 10 years on average, such decisions should be taken by 2030.

Figure 7-17: **Maximum utilization rates in the scenarios, 2045**

Source: Öko-Institut



Utilization rate

- Potential expansion
- 75% – 100%
- 100% – 125%
- 125% – 150%
- 150% – 175%
- 175% – 200%
- 200% – 225%
- >200%

7.4.7.5 Scenario year 2045

For 2045, an additional investment volume amounting to approx. 70% of the NEP plan is calculated for the *energy transition reference* scenario, which corresponds to approx. € 23.7 billion overall. In the *solar focus* scenario, the grid expansion needs that arise in addition to the NEP from 2025 onwards amount to € 24.7 billion overall, which corresponds to an additional investment volume of approx. 73% of the NEP. Compared to the additional investment volumes calculated for 2040, the increase in investment needs thus amount to about € 10.7 billion, with the result that the grid expansion needs of the two scenarios again roughly correspond or those of the *solar focus* scenario exceed those of the *energy transition reference* scenario. The expansion of PV power between 2040 and 2045, therefore, creates relevant additional grid expansion needs.

The mean value of all maximum transmission line overloads continues to be very comparable in the scenarios (*energy transition reference* scenario: 154%, *solar focus* scenario: 152%). Regional differences are observable in the extent of the overloads in the scenarios, as shown in Figure 7-17 and

Figure 7-18: **Maximum utilization rates of “mean max 20” in the scenarios, 2045** Source: Öko-Institut

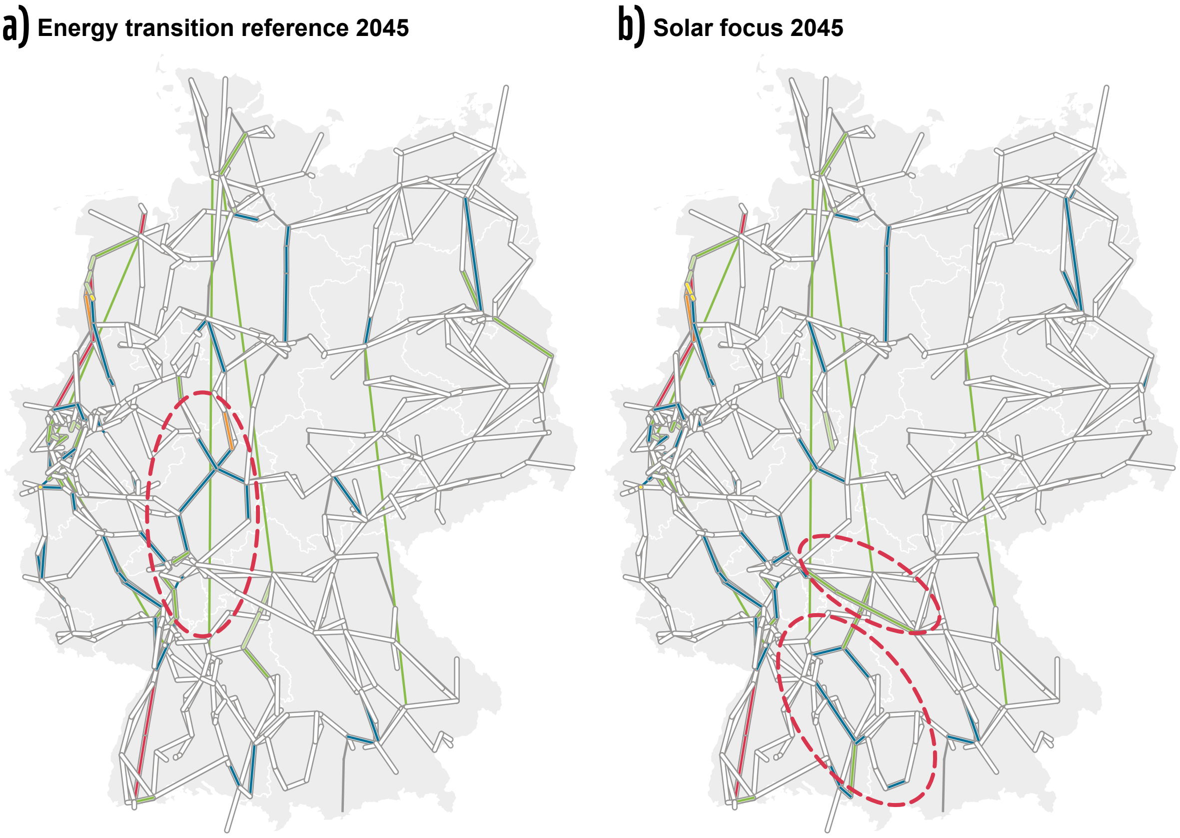


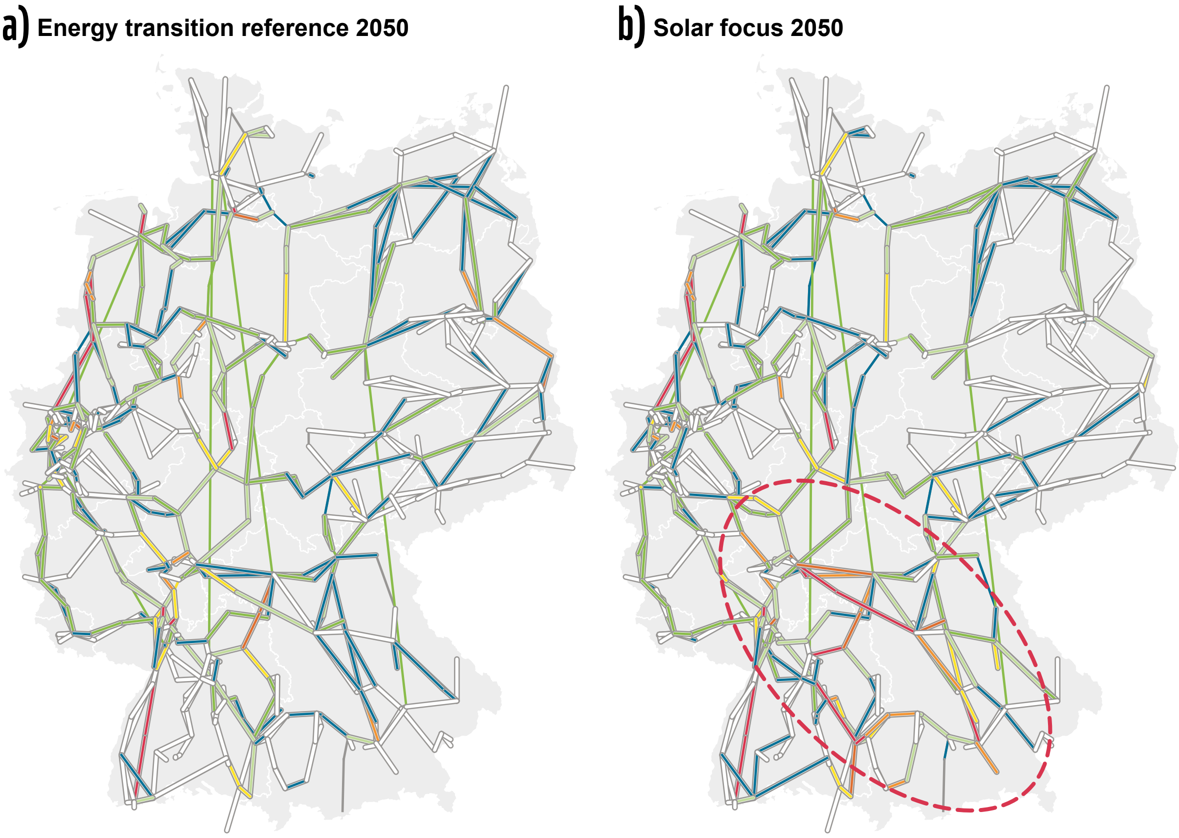
Figure 7-18. The north-south bottlenecks increase in the *energy transition reference* scenario. In the *solar focus* scenario, bottlenecks occur on a wide scale in the states of Bavaria, Baden-Württemberg and Hesse; these bottlenecks occur even in the “mean max 20”, which clearly shows that the high grid congestion occurs in a relevant number of hours in 2045. The grid expansion needs in the *energy transition reference* scenario predominantly arise in central Germany and align towards the north-south axis.

A large portion of grid congestion continues to occur independently of the scenarios and may be attributed to the expansion in offshore wind power. 84% of the transmission lines identified as overloaded in the *energy transition reference* scenario are also overloaded in the *solar focus* scenario; 82% of the transmission lines identified as overloaded in the latter scenario are also overloaded in the *energy transition reference* scenario.

As a result, it can be concluded that from 2045 onwards, relevant grid expansion needs are now path-dependent, i.e. they depend on the choice of expansion path and of the renewable energy technology mix.

Figure 7-19: **Maximum utilization rates in the scenarios, 2050**

Source: Öko-Institut



Utilization rate

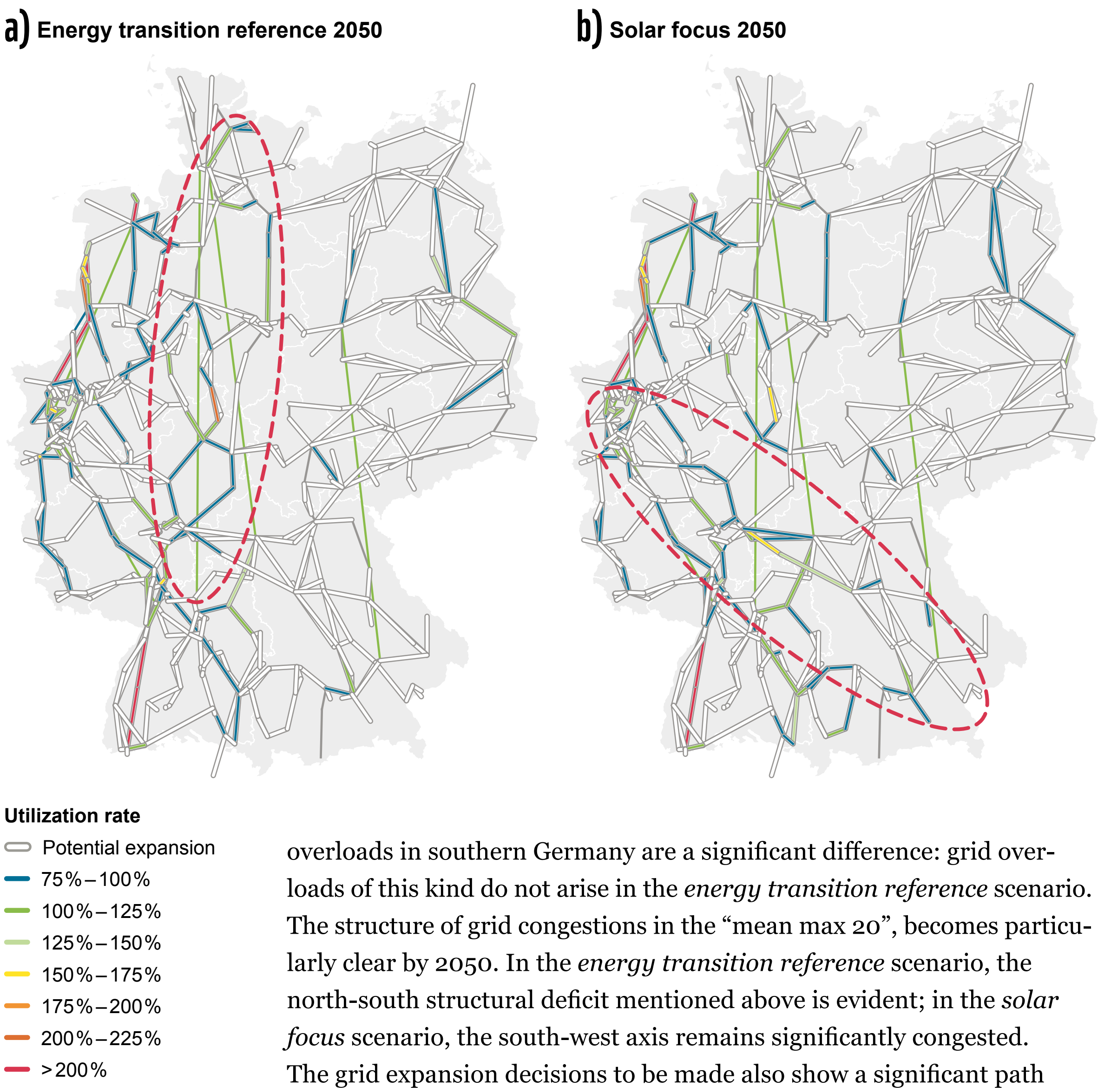
- Potential expansion
- 75% – 100%
- 100% – 125%
- 125% – 150%
- 150% – 175%
- 175% – 200%
- 200% – 225%
- > 200%

7.4.7.6 Scenario year 2050

By 2050, an additional investment volume amounting to approx. 130% of the NEP is calculated for the *energy transition reference* scenario, corresponding to approx. € 43.9 billion in total. In the *solar focus* scenario, the grid expansion needs that arise from 2025 onwards in addition to those in the NEP amount to € 46.4 billion overall, corresponding to approx. 137% of the NEP. In the long term, the grid expansion needs are higher in the *solar focus* scenario than in the *energy transition reference* scenario, although this occurs only in the later scenario years – thus at a time when there is a certain percentage of PV systems in the electricity generation system.

The mean value of all overloads over the maximums of transmission lines in both scenarios is still very comparable (*energy transition reference* scenario: 154%, *solar focus* scenario: 157%). Regional differences are observable in the extent of the overloads in the scenarios, as shown in Figure 7-19 and Figure 7-20. When the maximum capacity utilizations of the scenarios are compared, the substantially larger and wide-scale grid

Figure 7-20: **Maximum utilization rates of “mean max 20” in the scenarios, 2050** Source: Öko-Institut



overloads in southern Germany are a significant difference: grid overloads of this kind do not arise in the *energy transition reference* scenario. The structure of grid congestions in the “mean max 20”, becomes particularly clear by 2050. In the *energy transition reference* scenario, the north-south structural deficit mentioned above is evident; in the *solar focus* scenario, the south-west axis remains significantly congested. The grid expansion decisions to be made also show a significant path dependency for 2050.

Nevertheless, a large portion of grid overloads still occur independently of the scenarios and may come about from the increase of offshore wind power. 78% of the transmission lines identified as overloaded in the *energy transition reference* scenario are also overloaded in the *solar focus* scenario; 73% of the transmission lines identified as overloaded in the latter scenario also apply to the *energy transition reference* scenario.

On the one hand, this shows that by 2050 there is a substantial need for grid expansion, which can essentially be attributed to the expansion of renewable energies and occurs independently of the dominant renewable energy technology on an aggregated level. These grid expansion needs are significantly beyond those planned as a maximum in the NEP up to 2035.

In addition, the analyses have demonstrated that these grid expansion needs do not arise from the operation of coal-fired power plants, as the phasing-out of coal-fired electricity generation begins in the short term in both scenarios and is completed in 2035.

Overall, then, the grid expansion needs seem largely to arise independently of the scenarios. From 2035 and at the latest from 2040 onwards, however, a significant portion of grid expansion needs that arise depend on the development path of the regionalization of renewable energies. Since grid expansion projects involve an approx. 10-year planning period on average, a decision on the exact parameterization of the renewable path should be made by 2030 at the latest.

7.4.7.7 Sensitivity of *solar focus* in 2050 with and without optimization of PV self-consumption

To assess the advantage of a high share of roof-mounted PV systems with self-consumption storage in the context of grid expansion needs, a sensitivity analysis was conducted for 2050 in the *solar focus* scenario in the event that the option of PV self-consumption storage is not used at all.

Figure 7-21 shows the maximum utilizations of the transmission lines in the two scenarios. As a general rule, access to PV storage for self-consumption has no significant influence on the resulting maximum grid load if used exclusively to meet own electricity demand.

For the *solar focus* scenario with PV self-consumption systems, an investment volume of € 46.4 billion in 2025 was calculated for the grid expansion needs arising in addition to those in the NEP. This total corresponds to approx. 137% of the NEP for 2025. In the sensitivity of the scenario without PV self-consumption, the additional grid expansion needs – € 45.9 billion, corresponding to 135% of the NEP – are only slightly lower than the expansion needs resulting from a comparatively high number of PV systems with self-consumption in the electricity system.

From the perspective of the electricity system, then, it can be concluded that PV systems with self-consumption storage does not contribute to a reduced need for grid expansion as long as such storage is used under

Figure 7-21: **Maximum utilization rates in solar focus scenario with and without PV self-consumption systems, 2050**

Source: Öko-Institut

the premise of maximizing self-consumption. The additional flexibility in the electricity system is, therefore, not relevant to the grid. In spite of the high number of PV systems with self-consumption storage, power flows that induce additional grid expansion cannot be avoided. There can be many reasons for this:

- Although an electricity flow of 27.3 TWh is avoided by using intermediate storage to meet household demand, this can be overcompensated by a maximum of 30.9 TWh of industrial or tertiary sector demand that arises at the same node, which was met by PV electricity generation without self-consumption but now has to be supplied from other sources.

  - The visible yellow shading in the positive area represents the portion of PV electricity generation that can be stored in intermediate storage (30.9 TWh). The stored electricity is then used to meet the remaining household demand. This is possible in the *solar focus* scenario to the extent of 27.3 TWh.

- The utilization of the extra-high voltage grid avoided by using PV self-consumption storage may tend to arise at times when the grid is not being heavily used.

It should be noted, however, that the analysis did not consider whether there would be a positive benefit for the electricity system in general and the extra-high voltage grid in particular if the entire or at least the remaining storage capacity of the PV self-consumption storage were used for system optimization. If the storage were used for market or grid purposes (and would therefore be included in a regional or central coordination regime), a system benefit would result as a matter of course. However, such a use is not (yet) apparent in the incentive systems predominantly under discussion.

7.5 Cost aspects
7.5.1 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 meet demand. These prices thus predominantly depend, in the short and medium term, on fuel and CO_2 prices and, especially in the medium and long term, on the share of renewable generation options that have short-term marginal costs that are close to zero, i.e. above all the share of wind and solar power generation.

The effects of the different paths for expanding renewable electricity generation on wholesale electricity prices in Germany are shown in Figure 7-22. The prices calculated by the model were applied to the short-term marginal costs of a modern combined cycle power plant (CCGT), which arise based on the fuel and CO_2 price assumptions for the respective scenario year.[27] Using this approach, the market environment conditions assumed for the model calculations can be abstracted; and the influence of paths for expanding renewable power generation can be considered in isolation.

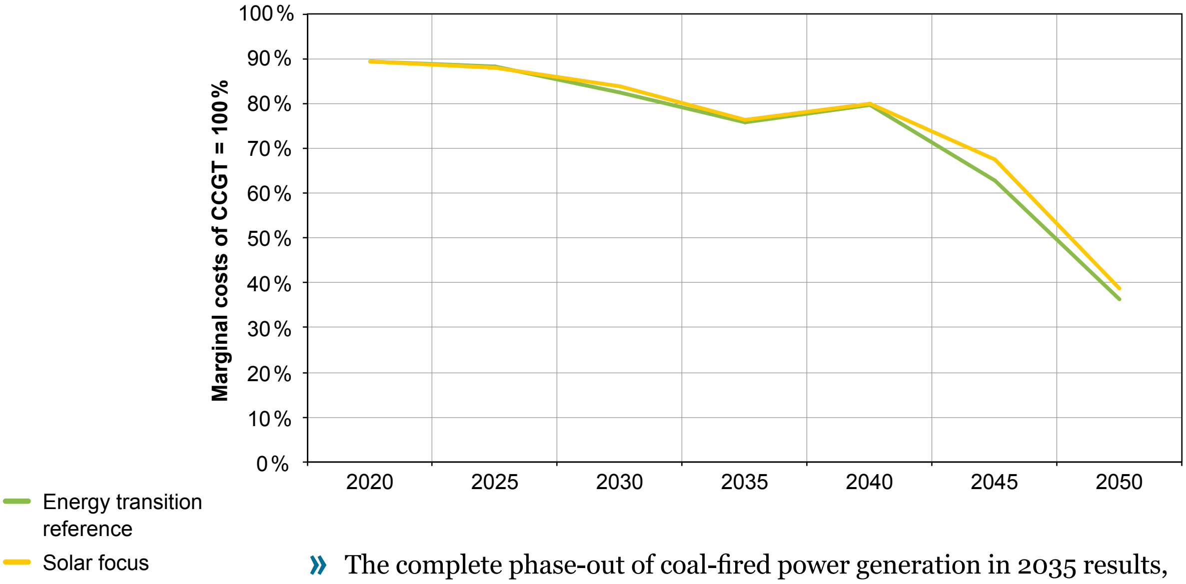
- Firstly, the results make very clear that the targeted expansion of electricity generation based on renewable energies has a very pronounced impact on wholesale electricity prices.

- This applies initially to the period up to 2035, during which the wholesale electricity prices in both scenarios steadily decrease.

27 The price is calculated as 44 €/MWh in 2020, 61.50 €/MWh in 2030, 83 €/MWh in 2040 and 94 €/MWh in 2050.

Figure 7-22: **Effects of different paths for expanding renewable electricity generation on wholesale electricity prices, 2020–2050**

Source: Calculations by Öko-Institut



» The complete phase-out of coal-fired power generation in 2035 results, in the short term, in a slight increase in wholesale electricity prices as natural gas-fired power plants then become price-setting in all hours in which fossil-fired power plants still have a price-setting effect.

» Due to the continued huge growth in renewable electricity generation, wholesale electricity prices decrease significantly again from 2040 onwards and are more than 60% below the short-term marginal costs of a natural gas power plant in 2050.

» The differences between the wholesale electricity prices calculated for the *energy transition reference* and *solar focus* scenarios are negligible for the period up to 2040 and are very low thereafter. The somewhat lower electricity prices for the *energy transition reference* scenario result from the wind availability, which largely corresponds with the residual load (i.e. the difference between electricity demand and renewable electricity generation) and thus has a stronger price-reducing effect than solar electricity generation concentrated in the midday hours.

Overall, the output-specific expansion path for renewable electricity production has a substantially larger influence on wholesale electricity prices than regional differences in the mix of onshore wind energy and solar electricity generation within such an expansion path.

7.5.2 Development of system cost differences

Beyond the price-based classification of different changes in the power plant fleet, the development of wholesale electricity prices naturally shows only some of the economic effects resulting from the different paths for the transition to an electricity system based on renewable energies. From a regulatory perspective, the costs of the entire system must ultimately be borne by the end users, i.e. the electricity consumers.

Against this background, the system cost differences for the *energy transition reference* scenario and the *solar focus* scenario were calculated for those cost categories for which significant differences may arise due to the different scenario designs. System cost differences arise for the following, as shown in Table 7-3:

- the variable operating costs of the electricity generation system;
- the technology-specific investment costs for building new power plants based on renewable energy and the fixed operating costs for renewable generation options that arise independently of the technology and represent the overall fixed costs for the renewable generation ("Total RES generation");
- the investment costs and the fixed operating costs for flexibility options, i.e. batteries (short-term electricity storage) and hydrogen electrolysis plants (long-term storage of production peaks from renewable energies), which represent the overall fixed costs for electricity storage; and
- the investment costs for the additional expansion of transmission grids.

All investment costs were assessed over the life of the technology options as annuity capital costs with a calculatory interest rate of 5% and were included in the comparison.

Table 7-3: **Difference in system costs between *solar focus* and *energy transition reference* scenario, 2020–2050**

Source: Calculations by Öko-Institut

	2025	2030	2035	2040	2045	2050	2020 to 2050
	€ billion						
Variable operating costs	-0.02	0.02	0.09	0.08	0.13	0.11	1.83
Capital costs RES generation	0.03	0.32	0.34	0.07	0.63	0.05	7.31
Onshore wind	0.00	-1.12	-1.70	-2.47	-3.02	-3.82	-52.79
Offshore wind	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Roof-mounted PV	0.03	1.02	1.39	1.78	2.62	2.73	42.54
Ground-mounted PV	0.00	0.44	0.70	0.83	1.10	1.25	19.04
Other	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Operating costs RES generation	0.00	-0.03	-0.05	-0.07	-0.08	-0.12	-1.49
Total RES generation	**0.03**	**0.32**	**0.34**	**0.07**	**0.63**	**0.05**	**7.31**
Capital costs of storage							
Battery storage	0.02	0.15	0.27	0.38	0.50	0.59	8.38
Electrolysis systems	0.00	0.00	-0.04	-0.07	-0.06	-0.03	-0.93
Operating costs of storage	0.00	0.02	0.04	0.08	0.10	0.12	1.58
Total storage	**0.02**	**0.17**	**0.27**	**0.39**	**0.54**	**0.67**	**9.03**
Capital costs of transmission grid	**0.00**	**-0.00**	**-0.13**	**-0.17**	**0.05**	**0.15**	**-0.86**
System costs	**0.04**	**0.51**	**0.57**	**0.36**	**1.34**	**0.98**	**17.31**
discounted	0.03	0.30	0.27	0.13	0.37	0.21	6.30

Even though considerable uncertainties remain for cost estimates as regards these categories and above all for 2040 and 2050, an analysis of the differential costs between the two scenarios produces relatively robust results.

Table 7-3 shows the differences between the system costs of the *solar focus* scenario and the *energy transition reference* scenario for 2020 to 2050. A negative value for a scenario year indicates that the system costs of the *solar focus* scenario exceed those of the *energy transition reference* scenario. It should be noted that uncertainty about the parameterization of investment options increases over the period.

The system costs are calculated using the following assumptions and methodology:

- The variable operating costs of the electricity system come from the electricity market modelling and include fuel, CO_2 and other variable operating costs of the overall system subject to the market environment conditions assumed in the model (see chapter 4.2).

- The capital costs for renewable power plants and their fixed operating costs for the period up to 2030 were derived from Öko-Institut's current projections for EEG cost development (https://www.agora-energiewende.de/veroeffentlichungen/eeg-rechner-fuer-excel/). For the long-term trends, a long-term analysis conducted by Öko-Institut on the system cost development of the electricity sector was used (Öko-Institut 2017).

- An analysis of the current literature and an update of Öko-Institut's calculation model for the comparison study of system costs (Öko-Institut 2017) was carried out for the capital and operating costs of battery storage. This results in investment costs (including converters) of 592 €/kW for 2020, 222 €/kW for 2030 and 149 €/kW for 2050. The fixed operating costs are calculated on the basis of 2% of the investment costs. In 2030, the battery capacity reaches values of 13.4 GW in the *energy transition reference* scenario and 19.9 GW in the *solar focus* scenario. By 2050, the installed capacity of battery storage increases to 46.8 GW and 94.8 GW respectively.

- The assumptions in Öko-Institut (2017) were used to calculate the capital and operating costs of the electrolysis systems. The corresponding investment costs amount to 871 €/kW for 2030 and 494 €/kW in 2050. The installed electrolysis capacity was derived from the use of production peaks from renewable energies for hydrogen production in the model and from a discount of 3% on the maximum purchase. For 2040 onwards, this results in the total installed capacity of electrolysis systems amounting to approx. 16 GW in the *energy transition reference* scenario and to approx. 15 GW in the *solar focus* scenario.

- The additional investment needs for the transmission grid changes over the scenario time frame (see chapter 7.4.7). In the years up to 2040, the *solar focus* scenario brings about a slightly lower increase than the *energy transition reference* scenario. Overall, however, the differences remain very low.

All investments were allocated on an annuity basis for the lifetime of the different power plants, using a uniform discount factor of 5%. The methodology of the annuity calculation counteracts the increasing uncertainty about future developments over the scenario time period: payment flows in the distant future are strongly discounted and are therefore less significant.

The relevance of the different electricity system segments in the cost differences is calculated based on the total of all cost categories from 2020 to 2050.

» The largest cost difference arises for electricity storage. This is explained by, above all, the early and huge market penetration of battery storage in the *solar focus* scenario (driven by, among other things, the focus on PV self-consumption systems and battery storage). The additional investment needs that thereby arise in the *solar focus* scenario are only partially compensated by the increase in investment needs for electrolysis systems in the *energy transition reference* scenario.

» The additional system costs arising for electricity generation plants in the *solar focus* scenario are lower than the storage costs. They are mainly due to the strong focus on roof-mounted PV systems, which initially cause higher costs. The lower investment needs arising for wind power plants in the *energy transition reference* scenario can only partially compensate the increased investment needs brought about by PV systems in the *solar focus* scenario.

» All other differential costs that are considered (variable operating costs, transmission grids) play only a minor role in system cost differences.

It was not possible in the scope of this study to consider the cost differences arising from the need to expand distribution grids. However, previous studies which address these costs (Öko-Institut 2017; Fraunhofer ISI et al. 2017a; 2017b; 2017c; 2017d) do not suggest that its inclusion in the analysis would fundamentally change the quality of the overall results.

The additional system costs in the *solar focus* scenario total approx. € 17 billion for the scenario time frame overall. The total system costs (including existing grids, backup capacities, etc.) are roughly estimated to total approx. € 64 billion in 2030 and approx. € 80 billion in 2050. This means that the additional costs of the *solar focus* scenario remain at a very manageable level of approx. 1% to 1.5% of the total system costs.

Finally, an analysis of discounted cost trends from 2020 to 2050 allows the following conclusions to be drawn on the classification of the cost differences for this time period:

- » The cost differences for electricity generation tend to come about earlier than those for electricity storage. The remaining uncertainties thus tend to be lower.

- » Differences in the system costs for storage arise earlier for battery storage (especially in the *solar focus* scenario) than for the additional demand for electrolysis systems (in the *energy transition reference* scenario), with corresponding consequences for uncertainties in cost estimates.

- » Cost differences for transmission grids arise particularly early in the scenario time frame. As a result, these differences are likely to be robust, but remain of secondary importance from an overall perspective.

From an overall perspective, land use restrictions, grid expansion needs and system costs stand in a field of tension: a strong focus on the use of rooftops for PV generation (including self-consumption concepts) slightly reduces the land use needs that arise in addition to ground-mounted PV systems, but also leads to (slightly) higher system costs. However, the need for additional expansion of the (transmission) grids and for corresponding investments is not significantly influenced by the transition to a renewable electricity system as conceived in these scenarios; in any case, these needs would be influenced over time.

8 Conclusions and outlook

The long-term target of decarbonizing Germany's economy can only be achieved if the electricity sector brings about comparatively rapid and extensive reductions in CO_2 emissions. This is clear from both the high contribution made by electricity generation to total greenhouse gas emissions and that electricity applications can and must make a substantial contribution to the decarbonization of other sectors (electric mobility, heat sector, etc.).

A development path that is compatible with the Paris Agreement requires a rapid phase-out of coal-fired electricity generation. This was analyzed in the first study of the "Electricity System 2035+" project. There must also be a huge expansion in electricity generation based on renewable energies, especially wind and solar energy. This was the focus of the present study, which forms the second phase of the overall project.

For Germany a huge expansion of electricity generation based on renewable energies is needed in an environment in which, firstly, electricity demand will substantially increase (from 2030) due to new electricity applications, e.g. in the transport sector. Secondly, the expansion of renewable electricity generation will essentially focus on only three sources: solar energy (PV systems), onshore and offshore wind energy. Thirdly, as a result of the transition to solar and wind power generation, the need for flexibility options (storage, demand flexibility, etc.) will substantially increase. Fourthly, the expansion of renewable energies will lead to fundamental changes in electricity generation structures. This means that grid infrastructures will need to be adapted, which must be planned and implemented with sufficient lead time.

The expansion paths for electricity generation based on renewable energies examined in this study show that very different developments are possible for the future electricity mix. Based on the quantitive analysis of these developments, the different fields of tension in the strategies for expanding renewable electricity generation can be classified as followed:

- The share of renewable energies in electricity generation can be expanded in different ways. Although most current projections for renewable power generation primarily focus on increasing onshore wind power generation, considerably different developments (e.g. which focus much more strongly on solar power generation) are also possible and consistent with a view to technological and cost developments and restrictions beyond economic optimization.

- The expansion paths of the *energy transition reference* and *solar focus* scenarios can be implemented (assuming relatively conservative land use potentials) without restrictions to a very large extent. The respective land use amounts to an average of 2.3–2.5% of Germany's surface land area and can be realized in a nature-compatible way. Nevertheless, land availability is the restriction whose significance increases the most over the time period concerned. An expansion path that focuses on onshore wind power after 2030 can bring about situations in which the land potentials free of restrictions are exhausted; other land potentials would have to be tapped and high priority should be given to combined use of land for wind and solar power generation. The land potential for roof-mounted PV systems also has clear boundaries since there are limited rooftop areas available.

- In contrast to electricity generation from roof-mounted PV systems, electricity generation from onshore wind power plants and from ground-mounted PV systems involves greater land use competition. These options also have (very slight) cost advantages in terms of generation costs and the costs for flexibility options. However, the expansion of roof-mounted PV systems strongly depends on the willingness of building owners to install these systems on their rooftops and may involve higher transaction or programme costs. The potentials of roof-mounted PV systems considered in this study represent the optimistic end of conceivable developments in this respect.

- With a view to the differences in land use restrictions and (system) costs, however, it is clear that land availability constitutes a much tougher restriction for expansion paths than the system costs, which involve only relatively small differences.

- As is the case with the costs, the differences in transmission grid needs are (very) small, although they vary slightly in the different time periods. It should also be noted, however, that the grid expansion projects needed are clearly dependent on technological and regional expansion paths from 2040 onwards at the latest. With a view to the lead times needed for grid infrastructure expansion, key decisions on expansion paths have to be made by 2030 at the latest. A detailed quantification of these path dependencies should be included as part of a long-term scenario in the calculations for the Grid Development Plan.

- A strong focus on self-consumption strategies may be useful as regards the extensive exploitation of land potentials for roof-mounted PV systems, but it does not lead to lower expansion needs for transmission grid infrastructures. The use of the extra-high voltage grid avoided by large-scale self-consumption solar storage is compensated by a stronger grid use among other electricity consumers. In order to reduce grid expansion needs, solar storage would have to be used for grid purposes rather than to maximize self-consumption.

Land restrictions are decisive in the use of onshore wind power and ground-mounted PV systems. Actual land availability must acquire greater importance in analyses on the future development of Germany's electricity system; it should play a similar role as the current limits on sustainable biomass use.

Land subject to restrictions is also often very economically attractive for development of renewable electricity generation projects (wind potentials, irradiation levels, infrastructure connections, etc.). The resulting land use conflicts can only be solved to a very limited extent by general framework conditions and should therefore be addressed at the planning level. However, the basic planning structures for tackling these land use challenges must be considerably improved. This should be combined with urgently needed improvements in public participation (both planning and financial) so that a high level of (local and regional) acceptance for expanding the use of renewable energies can be ensured.

The quantitive analysis of land restrictions in this study can be classified as conservative in two respects. With a view to the wide range of assumptions currently available, the calculated land use needs are at the conservative end. However, the possible synergy effects from combined land use, which was not considered in this study, could reduce the estimated land use. To limit land use, it is helpful to combine land used for renewable electricity generation on the one hand and suitable infrastructural, agricultural or forestry uses on the other hand. This also applies to the combined use of land for wind and solar power generation.

In view of the clear restrictions on expanding onshore wind power generation and ground-mounted PV systems, the largest possible exploitation of roof-mounted PV power generation makes sense from the perspective of effective land use, even though it has clear limits and can involve (slightly) higher costs. This exploitation additionally depends on the investment willingness of the building and roof owners concerned. In this respect, framework conditions can have a supportive effect by stimulating use of self-consumption options. These can also lead, however, to sub-optimal use of existing rooftop potentials and (slightly) higher overall system costs.

In the field of tension between land restrictions, costs, robust expansion paths and, from 2030 onwards, grid expansion, the regionalization of expansion strategies is of substantial importance. This regionalization should be addressed in a much more targeted and proactive way than is the case today (regional tenders, etc.). By 2030 at the latest, the technological and district-specific portfolio of renewable electricity generation shows increasingly relevant path dependencies. Particularly with a view to these path dependencies, future grid development plans need to adopt a broader perspective. In order to establish the necessary robustness for individual projects of grid infrastructure expansion, broader development variants of the future electricity system should be considered in grid development plans than currently the case. Analysis of the spectrum of possible variants should include the development paths examined in this study. Variants beyond these (e.g. which have a substantially larger quantity of offshore wind power generation) should also be taken into account in defining the full spectrum of possibilities in grid planning.

Overall, there is also a need for the Grid Development Plan to include calculations of a long-term scenario for 2050 with corresponding reference years. For a robust development of transmission grids, the planning should be based on the target of a fully decarbonized electricity supply. The medium-term grid expansion needs for 2030 should also be developed with this long-term target in mind. In order to allow transmission system operators the room for manoeuvre to develop a long-term scenario for 2050 and to carry out robust grid planning, § 12a of the German Energy Industry Act *(Energiewirtschaftsgesetz)* should be modified accordingly.

For the next phase of transforming the electricity system to one based on renewable energies, quantitative analyses with high spatial resolution will (have to) play a much more important role than has been the case so far in decisions of political strategy, long-term planning of electricity grid infrastructure and other flexibility options (demand flexibility, storage, etc.). However, the quality and the relevance of the modelling conducted in many cases decisively depends on the availability of high quality data in high spatial resolution. In some areas (spatial distribution of demand, current status of electricity generation plants), important preparatory work has already been carried out in this respect. With regard to the largely restriction-free land potentials for wind and solar power generation, data sets are available in several cases. Aggregating this data at national level, however, produces land potentials that probably do not appropriately reflect the total spectrum of land use restrictions.

Therefore, it is imperative that a data set is compiled on the realistic land availability for onshore wind and ground-mounted PV systems at district level. This would allow all modelling conducted for the above-mentioned purposes to be close to the real situation and therefore robust. This land availability data could, for example, include different classifications for the land use for solar and wind power generation (e.g. largely restriction-free, soft restrictions, combined land use potentials). With the help of such a data set, the standards for pluralistic and (particularly in terms of sensitive input parameters such as land availability) robust modelling could also be improved. This could also then contribute to a substantial improvement in the quality and robustness of decisions made on energy and climate policy and on the corresponding infrastructure planning. The incorporation of the German federal states as well as regional and local authorities in the process of developing a robust data set for land availability may involve considerable additional work and is challenging in view of the allocation of powers, but could hugely improve the quality of the planning basis for expanding the use of renewable energies in Germany.

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Annex 1: Detailed tables of results

Table A-1: ***Energy transition reference*, 2015–2050**

Source: Calculations by Öko-Institut and Prognos

	2015	2020	2025	2030	2035	2040	2045	2050
Generation capacity	GW (net)							
Nuclear	12	8	-	-	-	-	-	-
Lignite	21	9	9	6	3	-	-	-
Hard coal	29	11	8	8	8	-	-	-
Natural gas	30	23	24	21	20	19	19	19
Other fossil	4	6	6	6	5	4	4	4
Hydro (excl. PSH)	6	6	6	6	6	6	6	6
Onshore wind	41	57	67	80	87	100	126	178
Offshore wind	3	6	18	27	33	39	45	51
Photovoltaics	39	56	75	87	105	122	138	154
Biomass	9	9	8	6	6	6	6	6
Other RES	-	1	1	1	1	1	1	1
Short-term storage (PSH etc.)	9	9	9	9	9	9	9	9
Reserves; DSM, imports	-	17	28	36	42	53	53	53
Total	**204**	**218**	**259**	**293**	**323**	**359**	**408**	**482**
Total firm capacity	121	99	99	99	99	99	99	99
Electricity supply	TWh (net)							
Nuclear	87	63	-	-	-	-	-	-
Lignite	143	51	40	28	10	-	-	-
Hard coal	107	59	46	38	34	-	-	-
Natural gas	59	50	49	35	34	41	39	41
Other fossil	21	17	15	13	10	8	6	4
Hydro	19	23	23	22	22	22	22	22
Onshore wind	71	102	130	163	186	222	278	388
Offshore wind	8	26	69	107	133	162	184	185
Photovoltaics	39	50	67	79	94	110	125	141
Biomass	50	45	40	26	19	19	19	13
Other RES	0	1	3	4	6	8	10	12
Total generation	**604**	**486**	**481**	**516**	**548**	**593**	**684**	**807**
of which renewable	187	247	331	401	461	544	639	763
Net electricity imports	-52	11	5	-35	-36	17	-10	-97
CO_2 emissions	million t CO_2							
Lignite	168	57	45	29	10	-	-	-
Hard coal	111	50	37	32	29	-	-	-
Natural gas	38	31	30	21	20	24	23	24
Other fossil	34	35	31	27	22	17	13	9
Total	**352**	**172**	**143**	**109**	**81**	**41**	**36**	**33**
Cum. CO_2 emissions	million t CO_2							
Lignite	168	762	1,015	1,200	1,299	1,299	1,299	1,299
Hard coal	111	492	711	885	1,036	1,036	1,036	1,036
Natural gas	38	190	342	470	574	683	800	916
Other fossil	34	210	373	517	639	736	812	868
Summe	**352**	**1,653**	**2,441**	**3,073**	**3,548**	**3,755**	**3,947**	**4,119**

Table A-2: ***Solar focus*, 2015–2050**

Source: Calculations by Öko-Institut and Prognos

	2015	2020	2025	2030	2035	2040	2045	2050
Generation capacity	**GW (net)**							
Nuclear	12	8	-	-	-	-	-	-
Lignite	21	9	9	6	3	-	-	-
Hard coal	29	11	8	8	8	-	-	-
Natural gas	30	23	24	21	20	19	19	19
Other fossil	4	6	6	6	5	4	4	4
Hydro (excl. PSH)	6	6	6	6	6	6	6	6
Onshore wind	41	57	67	67	67	70	88	115
Offshore wind	3	6	18	27	33	39	45	51
Photovoltaics	39	56	74	116	151	188	244	313
Biomass	9	9	8	6	6	6	6	6
Other RES	-	1	1	1	1	1	1	1
Short-term storage (PSH etc.)	9	9	9	9	9	9	9	9
Reserves; DSM, imports	-	17	28	36	42	53	53	53
Total	**204**	**219**	**257**	**310**	**350**	**396**	**476**	**578**
Total firm capacity	121	99	99	99	99	99	99	99
Electricity supply	**TWh (net)**							
Nuclear	87	63	-	-	-	-	-	-
Lignite	143	51	40	28	10	-	-	-
Hard coal	107	59	45	38	34	-	-	-
Natural gas	59	49	48	34	34	43	40	38
Other fossil	21	17	15	13	10	8	6	4
Hydro	19	23	23	22	22	22	22	22
Onshore wind	71	104	131	135	137	156	178	231
Offshore wind	8	26	69	108	133	162	180	189
Photovoltaics	39	51	70	107	147	177	225	288
Biomass	50	45	40	26	19	19	19	14
Other RES	0	1	3	4	6	8	10	12
Total generation	**604**	**488**	**484**	**516**	**553**	**595**	**680**	**799**
of which renewable	187	250	335	403	464	544	634	757
Net electricity imports	-52	10	2	-35	-39	17	-11	-92
CO_2 emissions	**million t CO_2**							
Lignite	168	57	45	29	10	-	-	-
Hard coal	111	50	37	32	29	-	-	-
Natural gas	38	30	29	21	20	25	23	22
Other fossil	34	35	31	27	22	17	13	9
Total	**352**	**172**	**142**	**109**	**81**	**42**	**36**	**31**
Cum. CO_2 emissions	**million t CO_2**							
Lignite	168	765	1,019	1,204	1,303	1,303	1,303	1,303
Hard coal	111	477	696	869	1,020	1,020	1,020	1,020
Natural gas	38	190	339	464	566	679	798	910
Other fossil	34	210	373	517	639	736	812	868
Summe	**352**	**1,642**	**2,427**	**3,054**	**3,528**	**3,738**	**3,933**	**4,101**

Annex 2: Distribution, land use and electricity generation of wind and solar power plants by German federal state

Table A-3: Installed capacity of onshore and offshore wind power plants and roof-mounted and ground-mounted PV systems, 2015, 2035 and 2050 Source: Prognos

	PV						Wind power					
	ground-mounted			roof-mounted			onshore			offshore		
	2015	2035	2050	2015	2035	2050	2015	2035	2050	2015	2035	2050
	GW											
Energy transition reference												
Baden-Württemberg	0	3	6	5	11	15	1	3	6	0	0	0
Bavaria	3	6	12	9	20	27	2	3	7	0	0	0
Brandenburg & Berlin	2	3	4	1	5	6	6	12	26	0	0	0
Hesse	0	1	3	2	4	6	1	3	7	0	0	0
Mecklenburg-Vorpommern	1	1	2	1	2	3	3	6	13	0	6	7
Lower Saxony & Bremen	1	3	5	3	9	12	9	18	37	3	21	33
North Rhine-Westphalia	0	3	6	4	11	15	4	8	17	0	0	0
Rheinland-Pfalz	0	1	3	1	4	6	3	6	12	0	0	0
Saarland	0	0	1	0	1	1	0	1	1	0	0	0
Saxony	1	1	2	1	3	4	1	3	6	0	0	0
Saxony-Anhalt	1	2	2	1	3	4	5	8	17	0	0	0
Schleswig-Holstein & Hamburg	0	1	2	1	3	4	6	11	23	1	7	11
Thuringia	1	1	1	1	2	3	1	3	6	0	0	0
Total	**11**	**26**	**48**	**29**	**78**	**107**	**41**	**87**	**178**	**3**	**33**	**51**
Solar focus												
Baden-Württemberg	2	4	12	6	22	28	1	2	4	0	0	0
Bavaria	3	29	72	11	31	34	2	3	5	0	0	0
Brandenburg & Berlin	2	2	2	1	5	11	6	10	17	0	0	0
Hesse	0	1	3	2	8	16	1	3	4	0	0	0
Mecklenburg-Vorpommern	1	1	1	0	1	4	3	5	8	0	6	7
Lower Saxony & Bremen	0	1	1	1	4	26	9	14	24	3	21	33
North Rhine-Westphalia	0	2	3	4	19	44	4	6	11	0	0	0
Rheinland-Pfalz	0	1	2	2	4	13	3	5	8	0	0	0
Saarland	0	0	0	0	2	3	0	0	1	0	0	0
Saxony	1	1	2	1	3	9	1	2	4	0	0	0
Saxony-Anhalt	1	1	1	0	1	6	5	7	11	0	0	0
Schleswig-Holstein & Hamburg	0	0	1	0	2	11	6	9	15	1	7	11
Thuringia	0	2	2	1	2	5	1	2	3	0	0	0
Total	**11**	**46**	**102**	**29**	**106**	**210**	**41**	**67**	**115**	**3**	**33**	**51**

Table A-4: **Land use of onshore and offshore wind power plants and roof-mounted and ground-mounted PV systems, 2015, 2035 and 2050** Source: Prognos

	PV						Wind power					
	ground-mounted			roof-mounted			onshore			offshore		
	2015	2035	2050	2015	2035	2050	2015	2035	2050	2015	2035	2050
	km²											
Energy transition reference												
Baden-Württemberg	7	48	103	21	67	87	35	167	333	0	0	0
Bavaria	42	103	188	32	118	159	63	206	414	0	0	0
Brandenburg & Berlin	33	50	66	4	29	38	280	644	1,255	0	0	0
Hesse	5	21	42	6	27	36	46	154	300	0	0	0
Mecklenburg-Vorpommern	10	18	26	2	12	19	126	276	540	0	442	442
Lower Saxony & Bremen	8	41	82	10	52	69	388	811	1,575	90	1,447	2,001
North Rhine-Westphalia	4	47	105	9	69	89	165	373	726	0	0	0
Rheinland-Pfalz	6	22	41	5	26	35	102	280	545	0	0	0
Saarland	1	5	9	1	6	8	10	27	51	0	0	0
Saxony	10	22	32	3	18	26	49	133	261	0	0	0
Saxony-Anhalt	14	26	36	2	17	26	218	542	1,068	0	0	0
Schleswig-Holstein & Hamburg	6	18	31	3	19	26	178	520	994	23	476	663
Thuringia	7	13	19	3	10	15	64	134	255	0	0	0
Total	**155**	**434**	**780**	**101**	**469**	**632**	**1,725**	**4,266**	**8,318**	**113**	**2,365**	**3,106**
Solar focus												
Baden-Württemberg	27	72	186	21	137	167	35	131	214	0	0	0
Bavaria	42	469	1,170	32	201	208	63	171	280	0	0	0
Brandenburg & Berlin	33	34	37	4	29	62	280	530	831	0	0	0
Hesse	5	22	42	6	51	98	46	124	197	0	0	0
Mecklenburg-Vorpommern	10	14	14	2	4	23	126	216	346	0	442	442
Lower Saxony & Bremen	8	14	22	10	24	155	388	645	1,026	90	1,447	2,001
North Rhine-Westphalia	4	28	43	9	114	266	165	299	474	0	0	0
Rheinland-Pfalz	6	26	32	5	26	79	102	226	357	0	0	0
Saarland	1	2	7	1	14	20	10	22	35	0	0	0
Saxony	10	23	30	3	16	52	49	107	171	0	0	0
Saxony-Anhalt	14	16	20	2	7	33	218	448	707	0	0	0
Schleswig-Holstein & Hamburg	6	8	10	3	12	61	178	428	661	23	476	663
Thuringia	7	26	38	3	14	32	64	108	167	0	0	0
Total	**175**	**752**	**1,651**	**101**	**648**	**1,258**	**1,725**	**3,454**	**5,466**	**113**	**2,365**	**3,106**

Table A-5: **Electricity generation of onshore and offshore wind power plants and roof-mounted and ground-mounted PV systems, 2015, 2035 and 2050** Source: Prognos

	PV						Wind power					
	ground-mounted			roof-mounted			onshore			offshore		
	2015	2035	2050	2015	2035	2050	2015	2035	2050	2015	2035	2050
	TWh											
Energy transition reference												
Baden-Württemberg	1	3	7	5	10	14	1	6	13	0	0	0
Bavaria	3	7	12	9	18	25	3	7	16	0	0	0
Brandenburg & Berlin	2	3	4	1	4	5	9	26	55	0	0	0
Hesse	0	1	3	1	4	5	2	7	14	0	0	0
Mecklenburg-Vorpommern	1	1	1	0	2	2	5	14	29	0	21	26
Lower Saxony & Bremen	1	2	5	3	7	9	15	40	82	7	87	142
North Rhine-Westphalia	0	3	6	4	9	12	6	17	36	0	0	0
Rheinland-Pfalz	0	1	3	1	4	5	4	12	26	0	0	0
Saarland	0	0	1	0	1	1	1	1	3	0	0	0
Saxony	1	1	2	1	3	4	2	6	12	0	0	0
Saxony-Anhalt	1	1	2	1	2	4	7	18	37	0	0	0
Schleswig-Holstein & Hamburg	0	1	2	1	2	3	10	26	54	2	28	48
Thuringia	1	1	1	1	1	2	2	6	12	0	0	0
Total	**11**	**27**	**48**	**27**	**68**	**93**	**67**	**186**	**390**	**9**	**136**	**216**
Solar focus												
Baden-Württemberg	2	5	13	5	21	27	1	4	8	0	0	0
Bavaria	4	31	76	10	30	32	3	6	10	0	0	0
Brandenburg & Berlin	2	2	2	0	4	9	9	20	35	0	0	0
Hesse	0	1	3	2	8	15	2	5	9	0	0	0
Mecklenburg-Vorpommern	1	1	1	0	1	3	5	10	18	0	21	26
Lower Saxony & Bremen	0	1	1	1	3	21	15	29	51	7	86	142
North Rhine-Westphalia	0	2	2	4	16	37	6	13	23	0	0	0
Rheinland-Pfalz	0	2	2	2	4	12	4	9	16	0	0	0
Saarland	0	0	0	0	2	3	1	1	2	0	0	0
Saxony	1	1	2	1	2	7	2	4	7	0	0	0
Saxony-Anhalt	1	1	1	0	1	5	7	13	24	0	0	0
Schleswig-Holstein & Hamburg	0	0	1	0	2	8	10	20	34	2	28	48
Thuringia	0	2	2	1	2	5	2	4	7	0	0	0
Total	**12**	**48**	**105**	**27**	**96**	**183**	**67**	**137**	**243**	**9**	**135**	**216**

Annex 3: Assumptions on development of power plant fleets in European neighbouring countries

Table A-6: Development of conventional power plant fleets in reported electricity neighbours (in MW)

Source: Öko-Institut

	FR	AT	BE	CH	CZ	DK	LU	NL	NO	PL	SE
	MW										
2020											
Backup	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Lignite	0	0	0	0	5,808	0	0	0	0	7,175	137
Natural gas	16,117	5,354	7,603	1,374	2,379	3,593	550	16,290	1,600	6,714	983
Nuclear	63,130	0	4,031	2,171	3,779	0	0	0	0	0	7,263
Biomass	3,960	1,376	1,335	488	661	2,233	20	1,439	4,706	1,410	3,000
Other	2,099	1,559	1,974	371	174	510	0	1,249	0	455	2,891
Oil	5,384	142	367	77	40	562	1	49	98	543	710
Hard coal	3,492	1,208	300	0	1,212	2,944	0	5,506	0	19,735	164
Total	**99,182**	**14,639**	**20,610**	**9,481**	**19,053**	**14,842**	**5,571**	**29,533**	**11,404**	**41,032**	**20,148**
2025											
Backup	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Lignite	0	0	0	0	5,072	0	0	0	0	6,611	25
Natural gas	34,894	5,291	7,790	2,847	3,379	901	550	13,802	1,600	6,914	983
Nuclear	44,158	0	4,031	1,193	3,779	0	0	0	0	0	5,475
Biomass	6,665	1,563	1,813	894	611	3,186	20	2,169	5,003	1,905	3,300
Other	2,099	1,559	1,974	371	174	510	0	1,249	0	455	2,891
Oil	2,551	77	367	77	40	281	1	49	96	491	422
Hard coal	3,492	1,208	37	0	1,212	2,636	0	5,506	0	14,238	164
Total	**98,859**	**14,698**	**21,012**	**10,382**	**19,267**	**12,514**	**5,571**	**27,775**	**11,699**	**35,614**	**18,260**
2030											
Backup	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Lignite	0	0	0	0	2,852	0	0	0	0	6,611	25
Natural gas	48,394	5,291	8,740	5,347	7,379	1,276	550	13,601	1,300	8,314	896
Nuclear	21,296	0	0	0	3,291	0	0	0	0	0	0
Biomass	9,370	1,750	2,290	1,300	560	4,140	70	2,900	5,300	2,400	3,600
Other	2,099	1,559	1,974	371	174	510	0	1,249	0	455	2,808
Oil	2,248	77	367	77	40	281	1	49	31	425	422
Hard coal	1,783	1,208	37	0	1,012	2,004	0	4,909	0	11,884	164
Total	**90,190**	**14,885**	**18,408**	**12,095**	**20,308**	**13,211**	**5,621**	**27,708**	**11,631**	**35,089**	**12,915**
2035											
Backup	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Lignite	0	0	0	0	2,360	0	0	0	0	4,177	25
Natural gas	57,294	5,252	11,856	7,811	10,379	914	550	13,050	900	10,514	896
Nuclear	8,612	0	0	0	1,916	0	0	0	0	0	0
Biomass	10,076	1,881	2,462	1,398	670	4,451	70	3,118	5,698	2,580	3,600
Other	2,070	1,559	1,974	371	174	510	0	1,249	0	455	2,730
Oil	2,207	56	344	41	40	281	1	49	31	425	422
Hard coal	655	114	37	0	812	1,299	0	4,508	0	11,244	164
Total	**85,914**	**13,862**	**21,673**	**14,621**	**21,351**	**12,455**	**5,621**	**26,974**	**11,628**	**34,395**	**12,837**

	FR	AT	BE	CH	CZ	DK	LU	NL	NO	PL	SE
	MW										
2040											
Backup	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Lignite	0	0	0	0	2,360	0	0	0	0	2,438	25
Natural gas	62,962	5,022	12,632	7,732	11,479	641	550	13,427	900	12,114	854
Nuclear	5,981	0	0	0	1,916	0	0	0	0	0	0
Biomass	10,783	2,013	2,634	1,495	780	4,761	70	3,335	6,095	2,760	3,600
Other	2,009	1,513	1,129	371	174	510	0	1,249	0	455	2,674
Oil	2,136	56	344	41	40	246	0	49	19	425	213
Hard coal	538	114	37	0	812	414	0	3,944	0	10,457	56
Total	**89,409**	**13,718**	**21,776**	**14,639**	**22,561**	**11,572**	**5,620**	**27,004**	**12,014**	**33,649**	**12,422**
2045											
Backup	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
Lignite	0	0	0	0	2,430	0	0	0	0	2,344	25
Natural gas	62,476	4,936	12,185	7,748	12,424	825	555	13,499	721	12,745	855
Nuclear	5,981	0	0	0	1,916	0	0	0	0	0	0
Biomass	10,783	2,013	2,634	1,495	780	4,761	70	3,335	6,095	2,760	3,600
Other	1,915	1,461	1,043	371	144	510	0	1,223	0	455	2,333
Oil	2,165	59	356	44	40	248	0	58	19	428	221
Hard coal	421	120	41	0	628	414	0	3,965	0	10,312	56
Total	**93,740**	**18,589**	**26,258**	**19,658**	**28,362**	**16,758**	**10,625**	**32,079**	**16,835**	**39,043**	**17,089**
2050											
Backup	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
Lignite	0	0	0	0	2,000	0	0	0	0	1,714	25
Natural gas	61,170	4,722	10,847	7,732	13,142	556	550	10,653	542	12,841	813
Nuclear	0	0	0	0	0	0	0	0	0	0	0
Biomass	10,783	2,013	2,634	1,495	780	4,761	70	3,335	6,095	2,760	3,600
Other	1,821	1,409	957	371	113	510	0	1,197	0	455	1,991
Oil	1,877	56	344	41	40	246	0	49	19	360	213
Hard coal	303	79	37	0	188	0	0	3,305	0	8,388	56
Total	**125,954**	**58,279**	**64,819**	**59,639**	**66,263**	**56,073**	**50,620**	**68,539**	**56,656**	**76,518**	**56,698**

Annex 4: Description of PowerFlex-Grid EU model

The PowerFlex electricity market model developed by Öko-Institut is a fundamental model for the European electricity market that is used to calculate the dispatch of thermal power plants, electricity feed-in from renewable energies, pumped storage power plants and flexible electricity consumption at minimum costs to meet electricity demand.

The dispatch model is designed as a linear optimization problem and implemented with GAMS software. The problem is solved using the CPLEX solver (simplex algorithm). The aim of the optimization problem is to minimize the sum of all variable costs. The feasible operation of power plants, storage and flexibility options is set using constraints.

The temporal resolution of the optimization problem is one hour; and the time frame is one calendar year (i.e. 8760 time steps). Within this time frame, solutions are calculated sequentially for each optimization period. This optimization period rolls through the calendar year with corresponding steps. The length of an optimization period can be freely adjusted; it ranges from 24 hours to 8760 hours. It is determined depending on the complexity of the problem and the desired time frame for the projections. In this project the 8760 hours of the year were calculated in one sequence. This generates a perfect foresight for the whole year.

The different power plants in Germany are mapped in detail using technical and economic parameters. If possible, thermal power plants are entered with plant-specific precision, given an individual efficiency and assigned to a transforming station and regionally to a federal state. Smaller thermal power plants, such as combined heat and power (CHP) systems, are grouped together according to technology and construction year and federal state and are ascribed characteristics with the help of type-specific parameters. These power plants can change their output over the entire output range based on fixed ramp rates. Pumped storage power plants are mapped based on their respective storage capacity and installed electrical capacity. Germany's current power plant fleet in the PowerFlex model consists of approx. 350 individual power plants and 90 technology aggregates overall. Biomass power plants that use biogas, wood or vegetable oil also form part of the thermal power plant fleet. Taking into account technology-specific restrictions, utilization of these power plants is flexible and part of the optimization process.

For variable renewable energy sources (run-of-river, offshore wind, onshore wind and photovoltaics), the maximum available electricity supply is based on scaled generic or historical hourly feed-in. The actual electricity quantity fed into the grid from hydro, wind and photovoltaic power plants is determined endogenously, i.e. variable renewable electricity can also be identified as surplus in, for example, the case of negative residual load and insufficient storage capacity.

The production pattern of combined heat and power (CHP) is based on a typical pattern for district heating and a uniform production pattern of industrial CHP plants. This produces a specific CHP pattern for each major energy source. For must-run power plants, such as blast furnace gas power plants or waste incineration plants, a uniformly distributed feed-in of electricity is assumed, which (unlike power plants based on renewable energies) cannot be curtailed.

Both the electricity demand and the fluctuating electricity feed-in from renewable energies are predefined in hourly resolution. The demand pattern consists of the grid load of the year concerned and a small share, assumed to be constant, for the consumption not included in the grid load.

A crucial aspect of the model is the generic representation of demand side flexibility based on storage and load management. Flexibility is thereby defined with the help of installed electrical capacity, storage capacity and the the load curve that needs to be fulfilled.

The following flexibility options were considered in this study:

» flexibilization of biogas and sewage gas power plants with the help of gas storage and increased CHP capacity;
» flexibilization of CHP power plants with the help of heat accumulators and additional heat sources (e.g. electric heating rod);
» pumped storage power plants;
» industrial load management;
» PV battery storage to optimize self-consumption;
» power-to-gas;
» electric mobility, a share of which is combined with smart charging.

In PowerFlex, the interactions with the European electricity market are taken into account by mapping the entire ENTSO-E region. Each country is represented as a grid node, which is connected via interconnectors, so that electricity imports and exports between countries are considered and optimized. The thermal power plants of other countries are divided into groups by technology and construction year and aggregated accordingly as generating units.

For Germany, the transmission grid can be mapped using either the DC approach for approx. 500 grid nodes (focus on resulting load flows) or the transport model approach for different regions (focus on economic power exchange). Using the DC approach, the load flows can be calculated during the market modelling with binding grid restrictions or subsequent to the market modelling or without binding grid restrictions. The result without binding grid restrictions constitutes a simplified load flow simulation in which grid bottlenecks do not influence the market result. The market result calculated under binding grid restrictions constitutes the result after successful redispatch and RES feed-in management. The grid results are calculated for each hour of the year. The DC approach was applied in this study since its focus is on load flows and the resulting grid expansion needs.

The grid expansion needs can be estimated, as in the present study, based exclusively on existing routes with the help of an ex-post evaluation of resulting load flows. More detailed results on grid expansion needs can be calculated with the help of iterative grid expansion. Based on a starting grid and a number of grid reinforcement and expansion options, a potential grid expansion project is tested and selected in each round for its ability to relieve pressure on the grid. Iterative grid expansion can allow for grid reinforcement and expansion options.

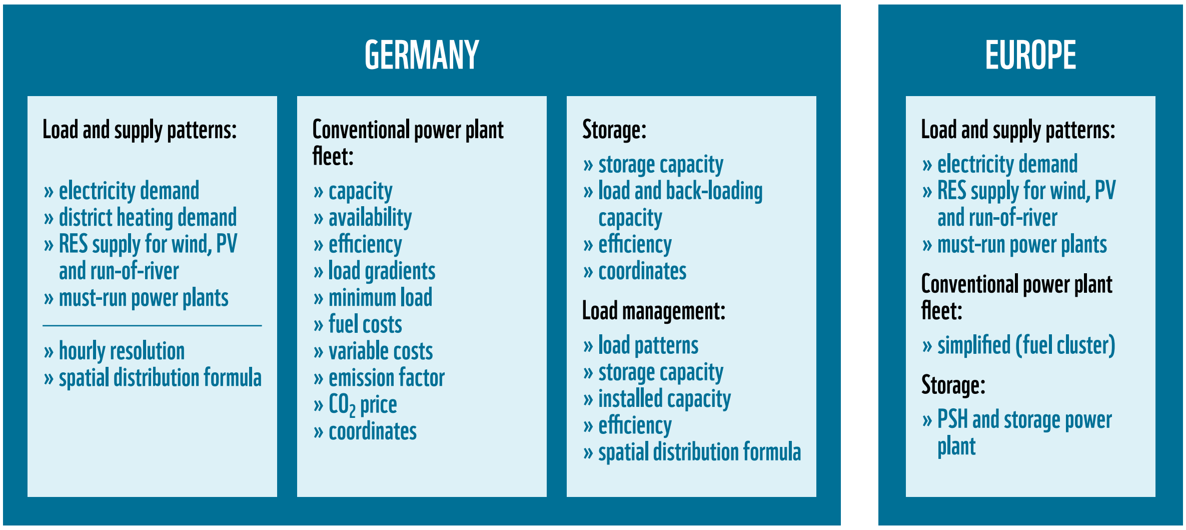
In order to balance fluctuating power generation from renewable energies (particularly wind energy and photovoltaics) and to be able to serve the grid load at any time, backup capacities that can provide additional output in the relevant hours are also included.[28]

28 The model incorporates a generic backup power plant that includes a large number of possible options such as gas turbines or agreements on load reduction in some hours.

The main input data for PowerFlex are shown in Figure A-1.

Figure A-1: Input data of PowerFlex-Grid-EU

Source: Öko-Institut



PowerFlex-Grid-EU provides the following relevant results (in hourly resolution):

- dispatch patterns of power plants (incl. hours of use and revenues on wholesale electricity market) and storage and flexible consumption,
- fuel mix
- CO_2 emissions
- losses due to storage and flexibility options
- RES curtailment
- electricity prices
- contribution margins of different power plants, storage and flexibility options
- utilization patterns of individual power lines
- grid expansion needs (number of transmission and distribution lines / power line kilometers / investment needs).

Annex 5: Load flow calculations and derivation of linearization

In a load flow simulation, the power flow on the individual lines is calculated for both the active power *(P)* and the reactive power *(Q)* using load flow equations. This is determined using the example of the load flow between nodes "k" and "m" based on the following equations:

$$P_{km} = \frac{(|U_k|^2 - |U_k| \cdot |U_m| \cdot \cos\Theta_{km}) \cdot R_{km} + (|U_k| \cdot |U_m| \cdot \sin\Theta_{km}) \cdot X_{km}}{R_{km}^2 + X_{km}^2}$$

$$Q_{km} = \frac{(|U_k|^2 - |U_k| \cdot |U_m| \cdot \cos\Theta_{km}) \cdot X_{km} - (|U_k| \cdot |U_m| \cdot \sin\Theta_{km}) \cdot R_{km}}{R_{km}^2 + X_{km}^2}$$

To estimate the load flow in the German extra-high voltage grid, the following assumptions are made which simplify the non-linear load flow to a linear correlation:

Θ_{km}:
The voltage angle between the voltage at node "k" and at node "m" is small. *($\sin\Theta_{km} \approx \Theta_{km}; \cos\Theta_{km} \approx 1$)*

Voltage drops:
The voltage profile is assumed to be flat. *($U_k \approx U_m \approx U$)*

Power losses:
It is assumed that the effective resistance is negligible compared to the reactive resistance of the power line *($R \ll L$)*. This means that there are no grid losses.

Taking into account the assumptions and the reciprocal relationship $b_{km} = \frac{X_{km}}{R_{km}^2 + X_{km}^2}$ the above load flow equation is simplified to a proportional relationship between the power flow and the phase angle of the voltage, for which the susceptance b_{km} is the proportionality factor:

$$P_{km} = \frac{(|U_k|^2 - |U_k| \cdot |U_m| \cdot \cos\Theta_{km}) \cdot R_{km} + (|U_k| \cdot |U_m| \cdot \sin\Theta_{km}) \cdot X_{km}}{R_{km}^2 + X_{km}^2} = b_{km} \cdot \Theta_{km}$$

$$Q_{km} = \frac{(|U_k|^2 - |U_k| \cdot |U_m| \cdot \cos\Theta_{km}) \cdot X_{km} - (|U_k| \cdot |U_m| \cdot \sin\Theta_{km}) \cdot R_{km}}{R_{km}^2 + X_{km}^2} = 0$$

Thus, the simplified load flow simulation only considers the active power flows and does not take into account any line losses. As a result, this methodology tends to underestimate the actual load of the transmission grid. The deviation between the results of an AC load flow simulation and a simplified DC load flow simulation is estimated to be approx. 5% of the AC load flow result.

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