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Analysis

Assessing power system adequacy in Germany and Europe, and lessons for China

Sino-German Energy Partnership

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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Content

Editorial

Policymakers and planners have long recognised the critical role of assessing capacity adequacy in maintaining electricity system reliability, which, in turn, is essential for economic stability and societal support for the ongoing low-carbon energy transition worldwide. The scale-up of wind and solar energy poses new challenges for power system planning. While systems with a high proportion of variable renewable energy are certainly compatible with reliable power supply—as some countries now demonstrate—they do entail more uncertainty and, therefore, more complex assessing and planning processes. Further, planners will have to incorporate new practices in fields such as electric vehicle charging and demand-side flexibility.

In 2021, China experienced power cuts and shortages in a number of provinces. While these outages had a variety of causes, those in September and October 2021 related primarily to market factors—namely, the mismatch between the high market price of coal and a fixed price for electricity produced by coal plants. As a result, many coal plants experienced physical fuel shortages and operated at low capacity. While this incident appears related mainly to market design rather than planning for system adequacy, any shortage or outage inevitably leads to calls for more reliable capacity on the supply side. Indeed, not only did the Chinese government respond to the shortages by raising power prices and capping coal mine profits but also with new rules designed to boost coal plant capacity. When old and less efficient coal plants retire, they should now go on reserve status, and the government will mandate coal power companies to operate plants at rates at least as high as in previous years. Government documents have increasingly prioritised energy security—especially the security of supply—which could accelerate the construction of new coal-fired capacity to meet peak loads.

The purpose of this report is to explain and illustrate how Germany and Europe are adapting their system assessment and planning processes to ensure that reliability and energy security are fully compatible with the retirement of conventional coal and nuclear power plant capacity. After all, Germany has one of the most reliable power systems in the world—the most recent system adequacy study for 2030 shows that Germany's loss-of-load-probability (LoLP) for that year is 20 times safer than the country's current standard,[1] even though Germany will shortly phase out its last remaining nuclear plants and most of its coal capacity by the end of the decade. However, since the analysis was based on assumptions derived from past German policy targets that have been changed in the meantime, future updated capacity adequacy assessments may arrive at slightly different results.

Germany also experiences periods known as the dark doldrums—times in the winter and fall when wind speeds fall and solar output ebbs. Indeed, Germany's seasonal downturn in wind and solar is far more pronounced than that of China, which experiences more consistent winter sunlight and where wind output typically reaches its peak in the colder months. Given that renewables already make up a sizeable share of their electricity production, it is critical that Europe and Germany incorporate weather uncertainty in capacity adequacy assessments. This goes along with modelling uncertainty around short-term outages of conventional plants, transmission lines and fossil fuel supplies, as well as long-term spikes in demand that might arise from climate events or vehicle electrification.

It is also important to model realistic levels of uncertainty in ways that do not bias the planning result towards installing more costly generation and storage rather than first prioritising relatively cost-efficient investments in transmission, cross-border electricity trade and demand-side flexibility.[2] As we show in this report, European methods for capacity adequacy assessment are already moving to incorporate more such measures, though this is at an early stage. And as more storage does come online, several recent studies of other markets suggest that a modest amount of storage—primarily of short duration, such as 4-hour storage—will go a long way towards ensuring that more of the full value of each MW of wind or solar capacity is available to satisfy peak loads.[3]

Lastly, although this report focuses on the technical aspects of European and German system adequacy assessment, the concepts discussed here are not just relevant to technical experts but also to policymakers. Power system planning and assessment exist in the realm of technical reports as well as in public policy. Policymakers interact with such assessment methodologies when setting high-level targets for renewables or carbon. When outages or shortfalls occur, experts and policymakers can use the results of these analyses to push back on simplistic calls for building "more reliable baseload energy" or one-size-fits-all mandates for all renewables to include costly on-site storage. Not only does getting the assessment right help keep the lights on, but it can also contribute to a more fruitful public discussion of the role and value of renewables in the energy transition. Hence, planners and policymakers should work to make the process open and comprehensible to a wider audience, even as its data requirements and methodologies grow more complex.

This report summarises the current and expected future power system planning and assessment practices in Germany and analyses the methodologies used in various publications in the last decade from relevant institutions responsible for power system planning in Germany. These include the German Transmission System Operators, the Federal Ministry for Economic Affairs and Climate Action (until the end of 2021, the Ministry for Economic Affairs and Energy), and the Federal Network Agency. In addition, it presents the methodology used by the European Network of Transmission System Operators for Electricity (ENTSO-E) for the assessments related to the European level. Both their results and the underlying methods are used for evaluations and methodology development in Germany.

As the report shows, the methodologies developed and applied in Germany have commonalities—particularly in moving away from deterministic calculations and towards probabilistic assessments of weather and other events, and expanding the geographical scope for analysis—and their methodologies seem to converge over time. Current debates indicate the need for including grid and system adequacy assessments, which have, until now, been provided mainly by the TSOs, in the overall capacity assessment. This development also confirms our expectation that the coal phase-out will lead to increased integration of capacity and grid adequacy assessments in Germany.

This report is one of many that examines the power system planning and assessment practices in the European Union (EU) that have implications for China and other countries in the transition to low-carbon energy systems. The November 2021 report by the EU-China Energy Cooperation Platform (ECECP), "ENTSO-E Grid Planning Modelling Showcase for China", illustrated the planning methodology for individual transmission lines and applied this methodology to a selected number of potential new lines in China.[4] Whereas the ECECP report looks primarily at transmission planning, this report looks at the broader issue of capacity adequacy—but the two are obviously related given the role of transmission in ensuring capacity adequacy within interconnected regions. In some respects, the two reports are complementary and can be read in tandem.

We hope that this study will help inform policymakers in China and elsewhere about the ongoing evolution of system adequacy planning in Germany and Europe and how these are developing in a direction that will make a positive contribution to the low-carbon energy transition. We believe that as China works towards an electricity system with renewable energy at its centre, sharing experiences and methodologies on system adequacy can serve as an inspiration for all parties, helping us not only ensure reliable power supplies but also helping policymakers and the public envision the establishment of a future energy system that is clean, reliable, and cost-efficient.

Sincerely,

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1 Introduction: Aims of the report, definitions and research questions

This report aims to explain the current and future use of quantitative methods in power system assessment in Germany. The most important aim of such assessment should be to establish a power system that meets economic and ecological requirements while maintaining the security of supply.

Security of supply encompasses two aspects:

- **generation capacity adequacy** and
- **grid and system adequacy**.[5]

With regard to capacity adequacy, investigations have examined whether and how supply and demand can be balanced within the electricity market in a particular period of time. This balancing can be determined by modelling electricity markets in one country or in a group of countries.[6]

For the sake of consistency, the report employs the term *capacity adequacy* as synonymous with both *generation adequacy* and *resource adequacy*, even if the authors of the referenced reports used other terms.

Grid and system adequacy deals with the stable operation of power grids. An important basic principle in grid planning and operation is known as n-1 security. This principle states that if a single generation unit or flexibility measure should fail, technical grid parameters, such as current, voltage, or frequency, must remain within certain tolerable ranges.[7]

This report is organised as follows: Section 2 discusses the methods for analysing capacity adequacy, while subsections 2.2.2, 2.2.4 and section 3 investigate grid and system adequacy. Section 4 compares all the methods from prior sections in a long-format table displaying their similarities and differences, strengths and weaknesses. Section 5 summarises the changes in methodologies expected in Germany due to the phase-out of coal and nuclear power. The chapter also addresses the possibility or necessity of other changes in current methodologies given the low-carbon energy transition underway.

The report answers the following major questions:

- How does Germany define security of supply, capacity adequacy and grid and system adequacy?
- Who are the main actors involved in the process of estimating and calculating capacity adequacy in Germany, and what are their responsibilities?
- How do German system planners estimate whether generation capacity, interconnection capacity and system flexibility (demand response, energy storage, power plant ramp rates) will be adequate to meet system load for all hours of the year over any relevant time periods from 1 to 10 years?
- How do German planners incorporate system elements such as grid flexibility, power plant flexibilisation and demand-side flexibility into capacity assessment?
- What quantitative metrics are used in Germany, such as effective load carrying capability (ELCC)?
- When assessing system adequacy over longer periods, how do system planners quantitatively value different forms of variable renewable energy (RE), variable RE and storage (hybrid), stand-alone energy storage and distributed energy storage in comparison to traditional thermal (coal and nuclear) generation sources?
- How is Germany's capacity reserve determined, how are plants compensated, what types of plants participate, and how will this change over the next 10 years?
- How will such calculations and valuations change in the next 10 years as Germany retires more coal and nuclear plants?
- What are the necessary changes to the methods in the German power system assessments?

2 Methods for quantifying capacity adequacy in Germany

2.1 Background on process, responsibilities and definitions

German TSOs, the BMWK and the BNetzA all use similar definitions for capacity adequacy. The BMWi report from 2015, prepared by Consentec and r2b energy consulting, describes capacity adequacy as a "long-term security of power balance in the supply system, i.e. in particular the provision of sufficiently available generation capacity for the balance between supply and demand in the electricity market at any time."[8] The last TSO report on power balance published in 2020 proposes assessing the level of capacity adequacy by calculating the difference between the reliable available capacity reduced by the load and the potential of demand-side management (DSM).[9]

The underlying methods to model and determine capacity adequacy differ among the institutions, as discussed in section 2.

The current discussion in Germany concerning capacity adequacy assessment and modelling focuses mainly on three questions:

- If and how the elements of probabilistic analysis can be better integrated/considered in the model?
- How can flexibility measures, such as DSM, cross-border electricity exchange and linkages between the gas and power sector be better integrated/considered in the model?
- How can the model better integrate grid and system adequacy?

Power system modelling theory makes a basic distinction between:

- **probabilistic approaches**, in which probability-based statements concerning capacity adequacy are made based on the interaction and potentially simultaneous occurrence of various generation-load situations, and
- **deterministic approaches**, in which firmly defined situations are considered separate from each other without considering their probability of occurring.[10]

The probabilistic approach aims first and foremost to better integrate uncertainties such as variable RE generation as well as outages at power plants or transmission lines. Probabilistic approaches also aim to better integrate flexibility into capacity adequacy modelling.

Since Germany lacks an adequate legal framework for many flexibility measures, such as flexible loads, present German methodologies based on the probabilistic approach neglect the impact and role of flexible loads and sector coupling.

The next section presents the current approaches of the German TSOs, the BMWi/BMWK and BNetzA in detail.

2.2 Relevant quantitative methodologies

2.2.1 German TSOs' methodology to estimate national power balance

From 2011 to 2015, the German TSOs were legally bound to produce a joint report on the security of supply in Germany. Currently, they continue to prepare such joint reports on a regular basis. The TSOs describe their methodology as the *national power balance*.

Until 2015, German legislation did not set any legal rules for the methodology of the reporting on security of supply. The TSOs based their analysis on a deterministic approach with probabilistic elements related to the availability of generation units and the changes in the load. These were based in turn on historical and projected data. The TSOs have continued to follow this approach in their later reports. This approach draws upon the methodology applied and further developed by ENTSO-E and its predecessors.[11] However, the focus of the German TSOs is only on domestic generation units and loads, including all units technically assigned to the German electricity system, without considering the effects of the European internal market. In addition, they investigate only concrete situations in the power supply at a defined point of time in the past and in the future based on historical data and projections, not on probable or conceivable situations.

The German TSOs' most recent report published in 2020 includes a review of the year 2018 and a forecast for 2019–2022. For each year, the TSOs choose one reference day for the investigation:

- 2018: 28 February 2018 at 7:00 p.m. (reference scenario based on historical data);
- 2019: The third Wednesday in December at 7:00 p.m. (reference scenario based on historical data);
- 2020–2022: The third Wednesday in January at 7:00 p.m. (future scenario based on projection).[12]

The report analyses the development from 2020 to 2022 based on two scenarios: with and without any coal phase-out. The phase-out scenario accounts for any power plants closures until 2022 in accordance with the Draft of the Coal Phase-out Act from January 2020[13] that foresaw a gradual phase-out of coal power through 2038 and became law in July 2020. Accordingly, the reference scenarios could be compared with the possible future developments, including the worst case situation—the coal phase-out, which was already planned but not yet officially adopted when the TSOs published their report.

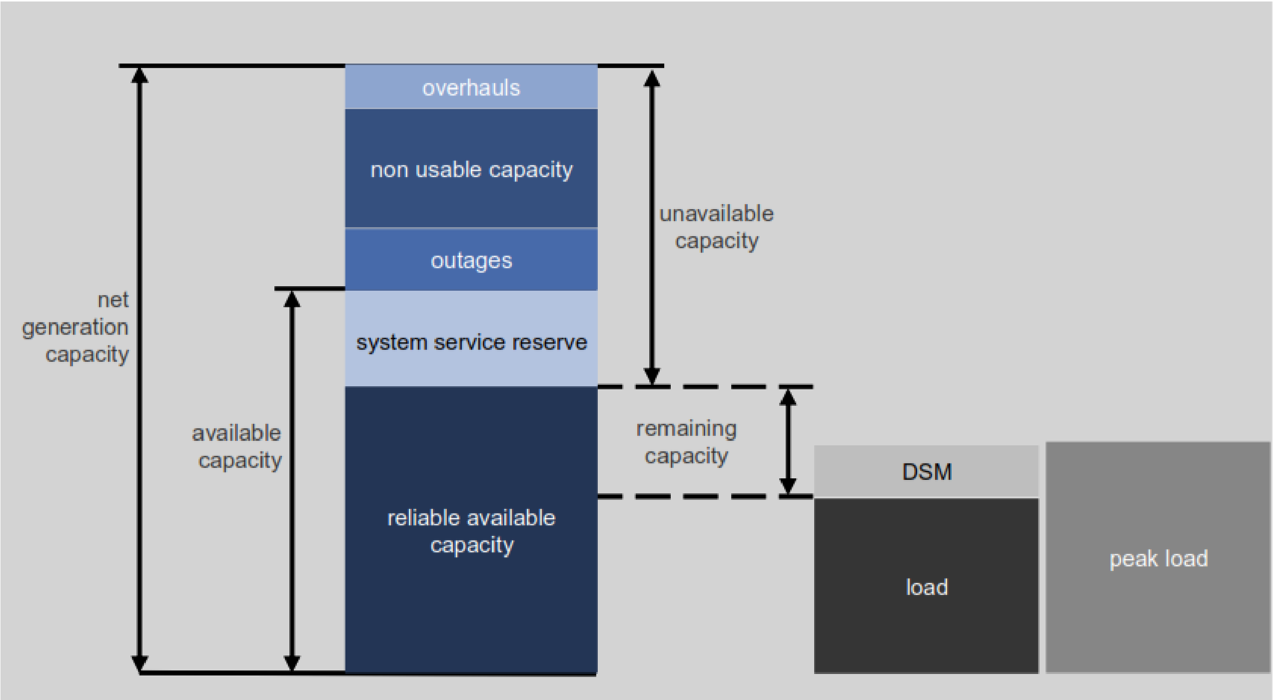
Quantitative metrics

Figure 1 diagrams the methodology used by the German TSOs. The general procedure consists of several steps, during which the main model metrics for each year are calculated, and different scenarios are considered:

1. **Reliable available capacity**, which deducts various unavailable elements (**unavailable capacity**) from the total amount of installed capacity (**net generation capacity**). Unavailable capacity is capacity not used to cover the load due to **overhauls**, fuel or weather-dependent outages (**non-usable capacity**), other unplanned **outages** as well as ancillary services (**system service reserve**).
2. Calculation of the highest load likely to occur in Germany **(peak load)**.
3. Calculation of the load reduction potential **(DSM potential).**
4. Calculation of the **remaining capacity (or marginal capacity)**. This is the difference between **reliable available capacity** and the **load** reduced by **DSM potential** at the annual **peak load**.

According to the TSOs' analysis, the capacity adequacy of the system depends on the amount of **remaining capacity (or marginal capacity)**. If the marginal capacity value is positive, there is sufficient generation capacity to cover the load, and the export of the surplus output is possible in the considered scenarios. If this value is negative, the load exceeds the reliable available capacity and, assuming that the load is not flexible, a certain import dependency exists in the scenarios that the TSOs considered.[14]

Figure 1. Methodology used by the German TSOs to estimate power balance



Source: Consentec, r2b energy consulting (2015)[15]

Quantitative value of different generation sources and other assumptions

When calculating the reliable available capacity, peak load and DSM potential, the analysis investigates probabilistic parameters. They are simulated by applying historical and projected data on peak loads, RE generation, the averaged availability of thermal power plants and pumped-storage power plants capacity estimations. However, with this approach, the TSOs do not assign any specific capacity values to individual technologies, as this value changes depending on the point in time considered.

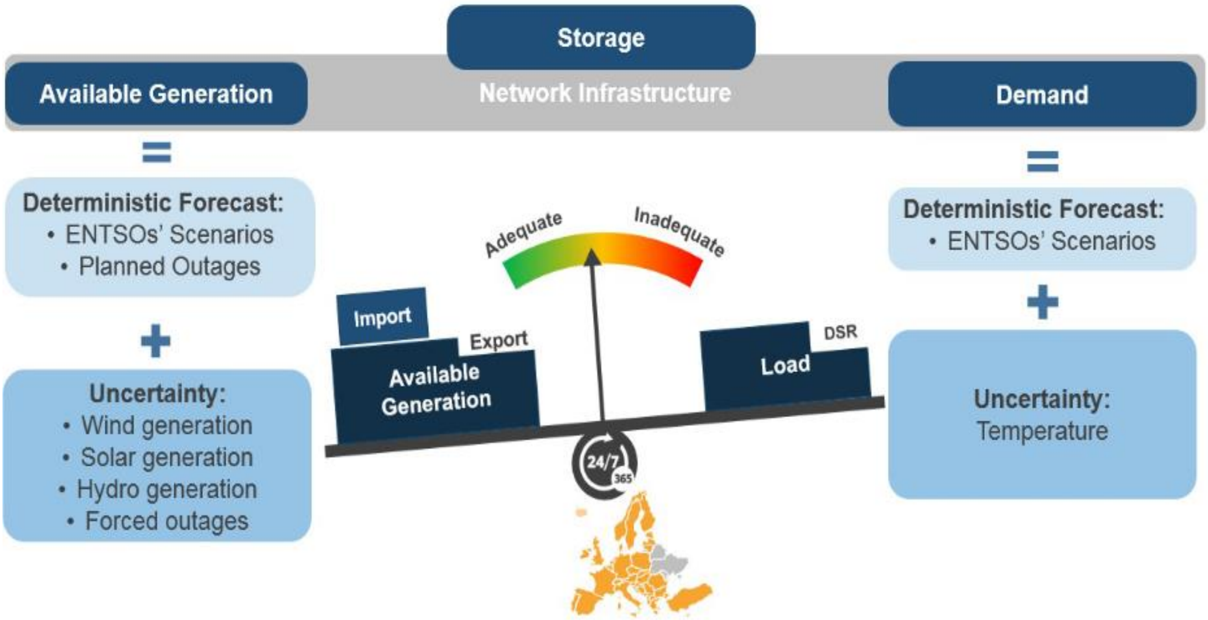
Only capacity that is available at least 99% of the time is considered as the available capacity of biomass and biogas power plants in the TSOs analysis. With regard to the availability of the conventional power plants, the TSOs assume that unscheduled outages occur to the annual peak loads, whereas the security level (cumulative probability for outages) amounts to 95%.[16]

2.2.2 ENTSO-E's methodology for resource adequacy assessment

In October 2014, ENTSO-E published an updated methodology for resource adequacy assessment.[17] ENTSO-E has decided to gradually depart from a deterministic methodology towards a probabilistic methodology to better model the volatility and uncertainties of the system as well as stochastic effects—mainly RE generation, forced outages and weather conditions. ENTSO-E recommends against country-specific assessments, instead stating assessments should cover a wide area of the EU and complement the local or national perspectives. Thus, the investigation should include a number of interconnected areas with limited transmission capacities. This enables a better and more systematic analysis of cross-border power imports and exports.

Hence, the new ENTSO-E methodology considers the generation side (available generation), the demand side and the grid side, including cross-border power exchange through interconnectors. This differs from the methodology of German TSOs, which neglects cross-border power exchanges. Figure 2 shows a simplified structure of the main elements of the ENTSO-E methodology as applied in the 2020 Mid-term Adequacy Forecast (MAF). The 2020 MAF marks the starting point for implementing the European Resource Adequacy Assessment (ERAA), the new pan-European monitoring assessment of power system resource adequacy.[18]

Figure 2. Main elements of the ENTSO-E methodology for resource adequacy assessment as applied in the 2020 MAF

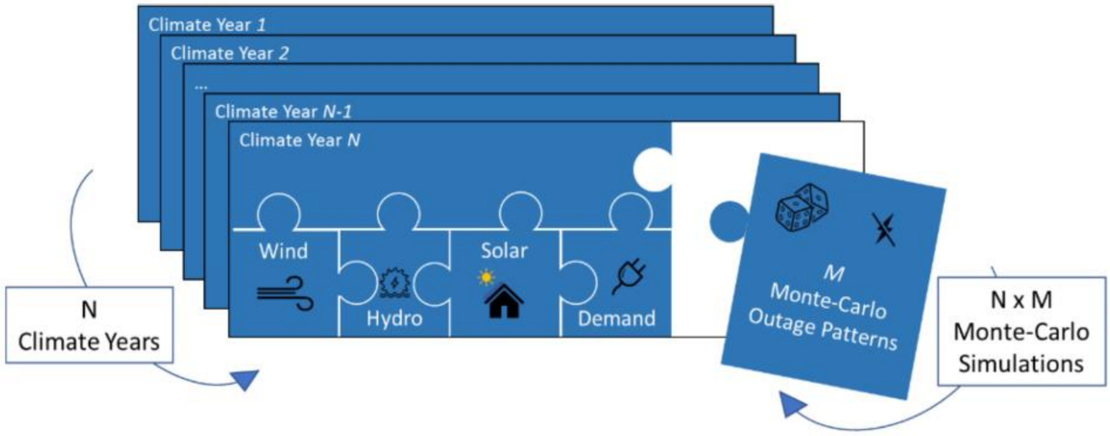


Source: ENTSO-E (2020)[19].

The main part of this methodology is a chronological hourly simulation of the whole interconnected system using a Monte Carlo (MC) simulation. According to the ENTOS-E website, "the core idea of the MC method is to use random input variable samples or inputs to explore the behaviour of a complex system or process under several possible future grid states".[20] In this simulation, for every point in time (hour), an optimisation procedure tries to cover the estimated load demand of each area using the generation capacity available both inside that area and in the other areas, according to their merit order and properly taking into account the interconnection constraints.[21] To do so, the modellers obtain a series of time points describing the system called Monte Carlo samplings. In these samplings, random input variables (RE infeed, load, forced outages of the generating units and interconnectors) are combined for a given year in order to obtain an optimisation result. RE infeed is determined based on the simulation of various climate conditions.[22] In the 2020 MAF, the target years include 2025 and 2030.[23]

This approach enables the evaluation of the stochastic effects, such as severe weather conditions, their duration and impact on RE output, as well as different load profiles during such extreme weather periods.[24] Figure 3 depicts the procedure.

Figure 3. Monte Carlo simulation principles for a given target year



Source: ENTSO-E (2020)[25]

Quantitative metrics
The ENTSO-E model analyses a large number of annual hourly simulations with various weather condition and power plant availability constellations and assesses the results with regard to different indicators. These indicators reflect the probabilistic character of the capacity adequacy. They include the following main indicators:

- **Loss of load expectancy (LoLE)**, which is the expected number of hours per year when the available generation cannot cover the load. It is expressed in hours per year.[26]
- **Loss of load probability (LoLP)**, which is similar to LoLE but expressed as a percentage or without any unit.[27] It represents the probability that the load will exceed the available generation in a certain period of time (week, month or year). The LoLP is also the probability that the Expected Energy Not Served (EENS, see below) occurs at the load peak. For example, if there were one week in a given year in which generation was insufficient, the LoLP calculated on a weekly basis would be equal to a probability of 1/52.[28] The LoLP can also be calculated on an hourly or daily basis.[29]
- **Expected energy not served (EENS) or loss of energy expectation (LoEE)**, which is the yearly load that cannot be covered due to insufficient generation. It is expressed in GWh.[30]

Quantitative value of different generation sources and other assumptions
The ENTSO-E methodology for resource adequacy assessment calculates RE generation based on weather data for a number of different years. This procedure enables mapping the broadest possible number of conceivable weather situations. In the MAF 2020, for example, three years of historical weather data were taken into consideration to model RE generation and electricity demand.[31] However, a specific capacity value for individual technologies was not assigned in this approach, as this value changes depending on the point in time considered due to differing weather conditions, power plant outages or grid bottlenecks.

2.2.3 BMWi monitoring of security of supply 2015–2021

In 2015 and 2019, the BMWi commissioned two reports with the aim to develop a methodology for capacity adequacy.[32] These analyses became a basis for the BMWi's monitoring of, and reporting on, security of supply. In April 2021, the BMWi published its last report on capacity adequacy based on the previously developed methodology.[33] As already noted, BNetzA took over the responsibility to monitor the security of supply in Germany in January 2021.

Both reports cited above expanded on the ENTSO-E methodology introduced in 2014 and described in the previous section. Thus, the BMWi and BNetzA had moved away from the methodology of power balance applied by German TSOs. The most important methodological aspects and findings of the BMWi reports will be described in the next subsections.

Transnational assessment of capacity adequacy

The so-called **transnational assessment of capacity adequacy** was developed in the first of the two studies (Consentec, r2b, 2015).[34] It is based on the probabilistic and cross-border approach, similar to the ENTSO-E methodology. It takes into account the stochastic characteristics of the system elements as well as the impact of the cross-border power exchange (imports/exports) and transmission restrictions. The report encompasses Germany as well as its geographical and electric neighbours.

Figure 4. Germany and its electric neighbours in the Consentec and r2b study (2015)

Source: Consentec, r2b (2015)[35]

The analysis used the same data as the best-estimate scenario (scenario B) from the ENTSO-E Scenario Outlook and Adequacy Forecast 2014[36] regarding the development of installed RE capacities, peak load, the conventional power park and the determination of further central regulatory parameters.[37] The main aim and result of the assessment were to determine the probability of full coverage of the load **(LBP)** by the available capacities within the considered geographical scope.

To assess the LBP, the study employed a computer-based stochastic and time-coupled simulation. This simulation mainly consisted of modelling the effects of a number of generation and load scenarios to test whether and how the residual load could be covered by either conventional generation or other sources, such as DSM, storage, imports or other capacities. This simulation was based on the assumption that the values of the individual input variables change over time, for example, due to changing weather conditions, power plant outages or transmission bottlenecks. Further optimisation of the model included the intertemporal (time-coupling) constraints of pumped hydro storage systems: their restricted reservoirs, pump capacity, the time distribution of natural inflows and their potential contribution to covering the load.[38]

The assessment determined values of different parameters and the LBP, not only for Germany but also for its neighbouring countries. Hence, the study could also determine the extent to which imports would be necessary and possible.[39] The study developed scenarios and results for three **forecast years:** 2015, 2020 and 2025.

Quantitative metrics

Figure 5 diagrams the methodology used by Consentec and r2b in the transnational assessment of capacity adequacy. The general procedure consisted of several steps, during which the modellers calculated the main model metrics:

1. Step 1 consisted of formulating assumptions (generation and load scenarios) and central regulatory parameters.
2. Based on step 1, the modellers developed three time series with an hourly simulation for both the **residual load[1]** and the **RE infeed** for each country and forecast year (2015, 2020 and 2025). The modellers used **historical load and weather data** from the base years 2010, 2011 and 2012 for each country to calculate the regional and time-based correlations between load and variable RE output.
3. In step 3, the modellers developed 333 random-based outage scenarios for each forecast year based on assumptions regarding the availability of conventional power plants. Each scenario included an hourly output profile for each power plant, considering the **typical outage rates** to determine the hourly availability of the power plants.
4. In step 4, the modellers combined the three time series of the residual load per forecast year (step 2) and the 333 outage scenarios per forecast year (step 3) with 999 **supply scenarios** per forecast year. Prior analysis showed that this number is sufficient.
5. In step 5, the modellers used the supply scenarios as input data to simulate cross-border matching of supply and demand. For all 999 scenarios, the simulation investigated whether the load can be covered at any time considering the essential technical and regulatory conditions, such as interconnector restrictions.
6. Finally, the modellers calculated the **LBP** for each forecast year and country considered based on the intermediate results.[40]

The **LBP** describes the probability that the available capacity can cover the load at a given point in time. This is defined as a short-term price-inelastic share of the load. It should be possible to cover the load without any further measures by the available generation, available DSM, or through the generation capacities available on the European electricity market.

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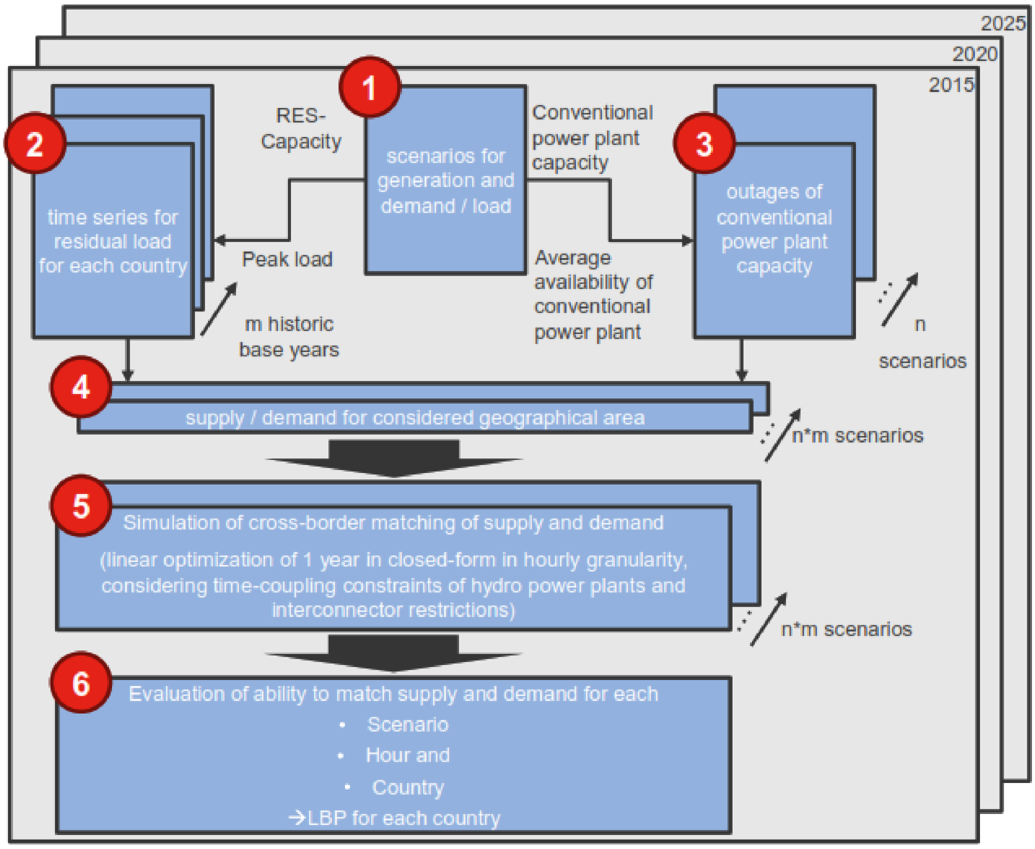
[1] **Residual load**: difference between the hourly electricity demand (load) and the electricity generated from RE.

Figure 5. Overview of the methodology approach of the transnational assessment of capacity adequacy



Source: Consentec, r2b energy consulting (2015), p. 14[41]

The analysis results show that load and generation could very likely be balanced at any time in Germany and its geographical and electric neighbours when taking into account the cross-border power exchange and, in particular, the portfolio effects within the region. The LBP was extremely high: almost 100% up to 2025. In practice, a technical system can never be completely available at a 100% probability, as there is always the possibility of extreme or unimagined situations beyond the scope of the simulations.

In any case, the investigations confirm the benefit of the transnational exchange of electricity and the necessity of the transnational monitoring of system adequacy, "regardless of the actual future development of capacity".[42]

Quantitative value of different generation sources and other assumptions

As with the ENTSO-E methodology (2014), the Consentec and r2b methodology did not assign any specific capacity value to individual technologies, as this value changes depending on the point in time considered. Therefore, the RE generation from wind and solar was calculated based on weather data for a number of different weather years. This procedure enabled mapping the broadest possible number of conceivable weather situations. The analysis took into consideration three historical weather years (2010, 2011 and 2012) to model RE infeed and the electricity load. With regard to conventional power plants, the analysis took into account generation unit outages as well as transmission bottlenecks.

For pumped hydro storage capacity, the analysis considered their intertemporal constraints by making assumptions on the reservoir size, the volume of natural inflows and their distribution over time. The volume of natural inflows (total volume per year and country) depends on the weather conditions. To determine inflows, the analysis employed the same historical weather years as for the load and RE infeed time series. Pumped storage systems and other storage power plants were aggregated to one pumped storage plant and one storage power plant for each country. [43]

In the case of biomass, the analysis only took inflexible generation into account when determining the residual load, treating biomass power plants the same as conventional thermal power plants.[44]

VS analysis model (2019)

In 2019, another analysis commissioned by the BMWi was published with the aim of assessing capacity adequacy in Germany. This study was prepared by r2b, Consentec, Fraunhofer ISI and TEP Energy and was based on a more extensive methodology than the previous study from 2015.[45] It introduced the VS analysis model to analyse the security of supply, which is based on the probabilistic and cross-border approach used in the 2015 study of Consentec and r2b and developed further in various aspects. In particular, the VS analysis model applied different quantitative metrics to assess the level of security of supply in Germany.

The methodological approach addressed the following two key questions:

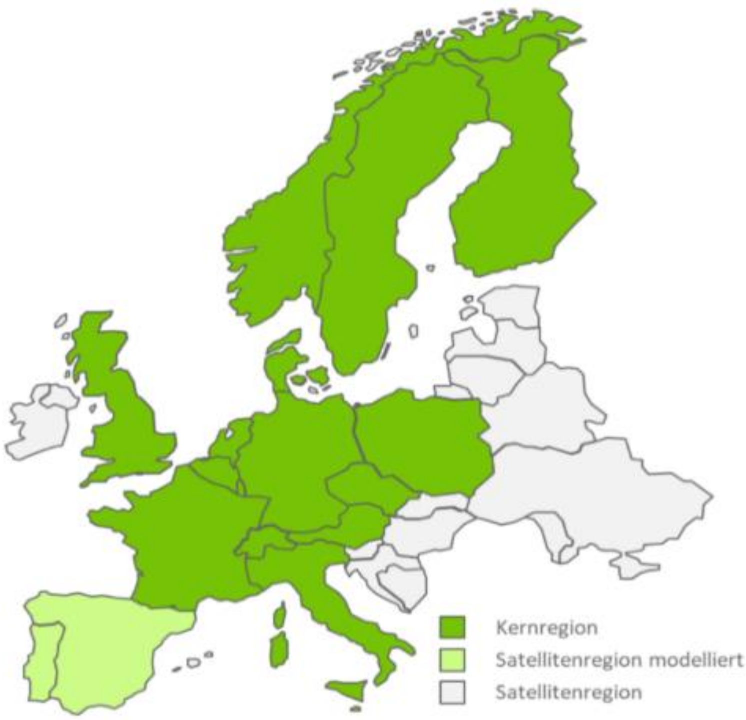
1. How will the European power system develop in the period under review?
2. Is the security of supply maintained efficiently in the European power supply system?

To answer these questions, the study needed to create scenarios for developing the power system and then evaluate the level of security of supply for each scenario based on the defined **reliability standard**.

The reference scenario (a best guess scenario without any additional policies related to climate change) was based on detailed research and comparison with other studies by mapping the existing legal framework conditions and policy goals. Alternative developments within the power system were examined through the sensitivity analyses of alternative scenarios.[46]

The model differentiated between core regions and explicitly modelled and non-modelled satellite regions (see Figure 5). The study defined Germany, its neighbouring countries, Italy, Great Britain and the Scandinavian countries as a core region, and the Iberian Peninsula as a modelled satellite region. The modellers mapped imports and exports between the countries of the core region as well as between the core and the modelled satellite region. Imports and exports between the satellite region and the core region were calculated in an aggregated manner.[47]

Figure 6. Modelled regions in the VS analysis model



Source: r2b energy consulting, Consentec, Fraunhofer ISI, TEP Energy (2019), p. 241[48]
Translation:
Kernregion: Core region
Satellitenregion modeliert: Modelled satellite region
Satellitenregion: Non-modellled satellite region

As mentioned, the main aim of the analysis was to determine the level of security of supply in Germany. To do so, the modellers mainly applied the LoLP indicator. The entire procedure to determine the indicators was similar to the procedure presented in the 2015 study by Consentec and r2b. The main differences (apart from the applied indicators) include:

- Five target years instead of three: 2020, 2023, 2025 and 2030.
- Five historical load and weather years instead of three: 2009, 2010, 2011, 2012 and 2013.
- 1,750 supply scenarios (simulation years) instead of 999. This corresponds to 15.33 million modelled hours per year.

For each of the 1,750 simulation years and the entire geographical region, the modellers determined whether the load in each bidding zone under consideration can always be covered. They took into account the available generation units and the available flexibility potential. Similar to the 2015 study, all relevant technical boundary conditions, such as power plant outages and available cross-border capacities, were also taken into account.[49]

The basic aim of the VS analysis model was to prove whether a system of equations and inequalities related to future system adequacy can be solved. This system of equations relates to the requirement that the load is covered at any time in a particular bidding zone, which requires the use of all different power supply sources, such as conventional power plants, different flexibility options, storage capacities and cross-border transmission capacities.[50]

If a solution can be found for a system of equations and inequalities described in this way, the entire load can be covered during a particular year in the entire geographical area under consideration. If the system of equations turns out to be unsolvable, a load balance is not possible in at least one bidding zone for at least one hour.

In order to determine the LoLP, which also requires the frequency, scale and location of the loss of load, the modellers proposed to apply linear optimisation.[51] The goal of this optimisation was to minimise the duration of the loss of load for the entire modelled year and region under consideration. Furthermore, in this optimisation, cross-border exchange is considered only when a bidding zone cannot cover its demand with its own generation units or flexibility measures. According to the authors, this kind of modelling differs from an economic simulation of the electricity market since it considers the included cross-border exchanges only when necessary for covering the load and not due to economic factors such as the availability of cheaper generation resources abroad. Therefore, it is possible to determine the contribution of the cross-border exchange for maintaining the security of supply.[52] Importantly, cross-border exchange in the VS analysis model has the function of an emergency measure, and its use cannot lead to a further loss of load in another bidding zone.[53]

As stated in the report, the results of the linear optimisation can be used to determine various indicators per bidding zone and year to assess the level of security of supply. Those indicators will be presented in the next section.

Quantitative metrics
The main indicators for assessing the security of supply in the VS analysis model are similar to those adopted by ENTSO-E. These indicators include (here the explanations are derived from the publication of r2b, Consentec, Fraunhofer ISI and TEP Energy (2019):

- **Loss of load probability (LoLP**), which describes the probability that the available generation will not cover the load of any consumer during all considered hours. It is expressed as a percentage or without a unit.[54]
- **Loss of load expectancy (LoLE)**, which represents the expected number of hours per year during which the available generation cannot cover the load. It is expressed in hours per year.
- **Expected energy not served (EENS) or loss of energy expectation (LoEE)**, which is the yearly load that cannot be covered due to the insufficient supply. It is expressed in GWh.[55]
- **System Average Interruption Duration Index (SAIDI)**, which describes the probability that the grid connection of a particular grid user/load is affected by an involuntary disruption of supply due to grid-related reasons. In reality, mainly failures in the distribution grid. To determine the SAIDI, both the duration of all disruptions within a year and the total lost load of all affected grid users/loads during the same year need to be determined. Next, the relationship between the lost load and the total load within a year must be calculated. Depending on the parameter of focus, SAIDI is expressed either in units of time (hours or minutes) per year or in the amount of affected load per year in relation to the total load.[56]
- **Power Market SAIDI**, which is the probability that a particular load will not be covered. It takes into account the flexibility potential of the grid users/loads and thus their voluntary loss of load due to load shifting or shaving, for instance). To determine the power market SAIDI in a particular bidding zone, the EENS need to be divided by the annual electricity consumption of all grid users/loads reduced by the annual integral of their potential for the voluntary loss of load.[57] It is expressed as a percentage or a time unit (such as hours per year).
- **Contribution of imports to ensure the security of supply**, which describes the effects of cross-border electricity trading on the security of supply. The EnWG (Energy Industry Act) explicitly requires considering these effects in monitoring the security of supply. The monitoring should provide information "to what extent imports contribute to ensuring the security of supply in Germany" (§63 Section 2 EnWG). However, for the VS analysis, it is only relevant whether imports are necessary to prevent the loss of load; only such imports are taken into account. Real or projected imports are irrelevant since they result from the economic ratio of the market participants, which means that under ideal market conditions, cross-border trading takes place when it is both technically possible and more cost-effective than inland generation or flexibility measures. In contrast, the VS analysis model differentiates between imports that are necessary for the security of supply and electricity trading for purely economic reasons.[58]

The main indicator of the VS analysis model for assessing the appropriate dimensioning of the power system in Germany is the LoLP.[59] The VS analysis determined a LoLP value of 0.06% as a **reliability standard[2]** in Germany. This value corresponds to an LoLE of 5 hours per year or to a Power Market SAIDI of about 5 to 10 minutes per year.[60] However, the reliability standard was updated in August 2021 and corresponds currently to a LoLE of 2.77 hours per year[61] (see also the subsection 2.2.4). This value is a reference value for the results of the adequacy calculations. Is the calculated LoLE value below the reliability standard, security of supply is given. For

[2] A **reliability standard** has to be applied by every EU member state that has implemented a capacity mechanism. It is a European standard for the economic efficiency in the electricity system. Its aim is to ensure that in the long term only those capacities are part of the capacity mechanism, whose costs incurred for the consumers do not exceed the benefits. The value of the reliability standard is a trade-off between the investment costs of new capacities and the willingness of electricity customers to pay for an uninterruptible power supply. The reliability standard applies to one bidding zone. Since Germany and Luxembourg are located in a joint bidding zone, they determine jointly the same reliability standard, which applies for both countries.

Germany, this has been always given in the existing monitoring of security of supply scenarios.[62]

Over the last few years, the SAIDI level in Germany has been between 12 and 15 minutes per year and grid user. This does not mean that every grid user in Germany experiences around 15 minutes of supply interruption each year. Rather, in individual cases, supply interruptions may last even longer, while many other grid users experience no supply interruption at all. Thus, the SAIDI is only an average value regarding all grid users.[63]

Quantitative value of different generation sources and other assumptions

Similar to the ENTSO-E methodology (2014) and the Consentec and r2b methodology (2015), the VS analysis model does not assign any specific capacity value to the individual technologies, as this value changes depending on the point in time considered. This is due to changing weather conditions, power plant outages and transmission bottlenecks. Therefore, RE generation from wind and solar was calculated in the model based on weather data for a number of different weather years as well as their expansion potential.[64] The generation capacity of run-of-the-river hydroelectricity was determined by taking into account the seasonal changes in water flow in the rivers. For geothermal plants, bioenergy plants, as well as landfill, sewage and pit gas, an hourly feed-in profile was determined based on historical feed-in values and historical full-load hours.[65]

In addition, the VS analysis model took into account further factors when determining the generation outcome, such as different market options, including direct marketing for RE, a market premium model for biogenic energy sources, the primary energy market and the heat market.[66]

The wholesale electricity market was modelled using a competitive market model in which supply and demand balance each other out at a certain market price in a particular bidding zone.[67] The model is based on the assumption that the market actors behave in line with rational expectations.[68] Another assumption is that cross-border electricity exchanges take place only if it is no longer possible to meet the demand with generation units or flexibility measures within the same bidding zone or the same country.[69]

Results of the assessment of capacity adequacy based on the VS analysis model (2021)

Based on the methodology developed and described in the BMWi report from 2019 and presented in the previous subchapter, the BMWi commissioned a study assessing capacity adequacy on the European electricity market that was published in April 2021.[70] The study developed a number of different future scenarios to determine whether the supply of electricity on the European electricity market will be sufficient to meet the demand at all times up to 2030.[71] The most important finding related to Germany was that supply would meet demand in all scenarios examined up to 2030 in both the baseline scenario as well as in two scenarios that anticipate more ambitious climate action, such as higher carbon prices and the increased electrification of transport, heating and industry.[72]

Experts defined a **reliability standard** for Germany at 99.94%.[73] This standard describes the state of equilibrium between the costs of provision of any additional generation capacity to meet the demand and the benefits for the consumers. The reliability standard of 99.94% means that it remains cost-effective to cover the demand in Germany for 99.94% of the hours in a year[74], which correspondes to a LoLP of 0.06%. In both the baseline scenario and the alternative scenarios, the LoLP was well below the cost-efficient level of 0.06%.[75] The LoLP in the reference scenario was 0% and in the alternative scenarios 0.003%. This result corresponds to an LoLE of 0 hours per year in the reference scenario or 0.25 hours per year in the alternative scenarios.[76]

The study compared the following alternative scenarios:

1. hypothetical energy-only markets in all countries under consideration, which means no additional subsidies for dispatchable generation;
2. increased sector coupling as a result of more ambitious climate protection with a moderate increase in CO_2 prices and electricity consumption;
3. increased sector coupling due to more ambitious climate protection with a higher CO_2 price increase and electricity consumption.[77]

The forecast gross electricity consumption in 2030 amounts to 615 TWh and 630 TWh for scenarios 2 and 3, respectively.[78] This is greater than previous estimations (567 TWh or 591 TWh), derived from the previous national climate target to reduce CO_2 emissions by 55% by 2030. The May 2021 change in the German climate target to further reduce CO_2 emissions by 65% by 2030 directly impacted electricity demand forecasts by 2030 due to the expected electrification in the transport, heat and industry sectors.[79]

The consulting company Prognos is preparing a detailed analysis of electricity consumption on behalf of the BMWi. Its first estimates show a consumption between 645 and 665 TWh in 2030; the mean value of the forecast is 655 TWh, which is only slightly above the maximum value estimated in the 2021 BMWi report on capacity adequacy. Another factor that may lead to a further increase in electricity consumption in Germany will be the expected implementation of the Green Deal at the European level, which is still pending.[80]

The most important results of the 2021 BMWi report can be summarised as follows:

- The German and European power systems have excess capacity.
- By 2030, additional combined heat and power (CHP) plants with a volume of approximately 15 GW will be built in Germany. Beyond that, no further market-driven expansion of gas-fired power plants is expected.
- By 2030, additional flexibility options (DSM or emergency power systems) up to around 2.5 GW will be available in Germany.
- The internal EU electricity market provides considerable balancing opportunities between countries and bidding zones.
- Imports are necessary to maintain capacity adequacy in Germany: up to 14 GW by 2030 (base scenario) and up to 24 GW by 2030 (scenario 3). The maximum necessary imports remain well below the technically possible import capacities of just under 35 GW in 2030.
- Imports are necessary for all considered European countries, and their volumes will increase over time.
- The current study by ENTSO-E shows higher availability of dispatchable resources in Europe by 2030, such as dispatchable power plants and flexibility options, than the scenarios of the 2021 BMWi report[81]: ENTSO-E expects 30 GW of additional capacity by 2030 in Germany,[82] compared to 17.5 GW in the BMWi report.
- Political action is still needed: cross-border coordination in case of simultaneous scarcities in several countries should be improved through better regulatory conditions for the day-ahead market.[83]

A word of caution is warranted: while its methodology remains sound, the report presented here is based on policy targets from 2020 that policymakers updated in late 2021. However, no new assessment of the security of supply has been published as of March 2022, the date of this report's publication.

2.2.4 BNetzA monitoring of security of supply since 2021

At the beginning of 2021, BNetzA took over the responsibility for monitoring the security of supply from the BMWi. It presented its first report on the monitoring of security of supply to the BMWi at the end of October 2021. Pursuant to section 63 of the EnWG, the BMWK (formerly BMWi) is responsible for drawing up an agreement on the report within the federal government before publishing it. At this point, the report has not yet been published.

Pursuant to section 63 of the EnWG, the federal government should also submit recommendations for action based on the BNetzA report to the German federal parliament *(Bundestag)*. This should have happened for the first time on 31 December 2021 and then at least every four years. However, it should be noted that the BNetzA's first report on the monitoring of security of supply analyses only one scenario: the *Best Guess* basis/reference scenario, which assumes the most probable development resulting from fulfilling the government's current energy policy goals.[84] The *Best Guess* scenario includes the previous German target to reduce greenhouse gases by 55% or 65% by 2030 (compared to 1990) as well as coal-fired power generation even after 2030. This corresponds to the German government's goals when the scenario was defined at the end of 2020 but does not adequately reflect the coalition agreement that is now available, including an intended target of 80% gross electricity consumption from RE. Accordingly, the study is insufficient for deriving recommendations for action based on the available security of supply monitoring from BNetzA. Therefore, according to BNetzA, it is more expedient to revise the security of supply monitoring by summer 2022 if possible in order to appropriately reflect the new goals of the coalition agreement. This would form the basis for tailor-made recommendations for action.[85]

Nevertheless, to complete this overview of the evolution of the capacity adequacy methodologies used in Germany, we would like to present the most important features of the monitoring of security of supply of the BNetzA. Our analysis is based on questions to BNetzA as well as information obtained at a stakeholder meeting organised by BNetzA.

BNetzA will likely use the same or similar methodology in its future reporting to the BMWK. However, the results of the future analysis may differ slightly from the results of the existing analysis since it will be based on other assumptions derived from new political goals, particularly the climate and RE targets.

For the reporting and modelling of the existing analysis, BNetzA selected a consortium of three external institutions: Consentec, the Institut für Energiewirtschaft und Rationelle Energieanwendung (IER) and Forschungsstelle für Energiewirtschaft e.V. (FfE).

Essentially, BNetzA bases its monitoring on the previous work and methodology developed in the reports commissioned by the BMWi. As in the VS analysis model presented in the previous subsection, the first step in the BNetzA model with regard to the power market is creating a forecast of the future power plant fleet. This forecast focuses on both Germany and its neighbouring electricity markets, particularly the German-Luxembourgish bidding zone. For assumptions regarding the future development, available historical data such as generation, load, heat demand, DSM potential, storage capacities and cross-border interconnection capacities are used. Furthermore, possible changes over the next 10 years are examined using an electricity market model in order to determine whether and to what extent shortages in the power supply can be expected.[86]

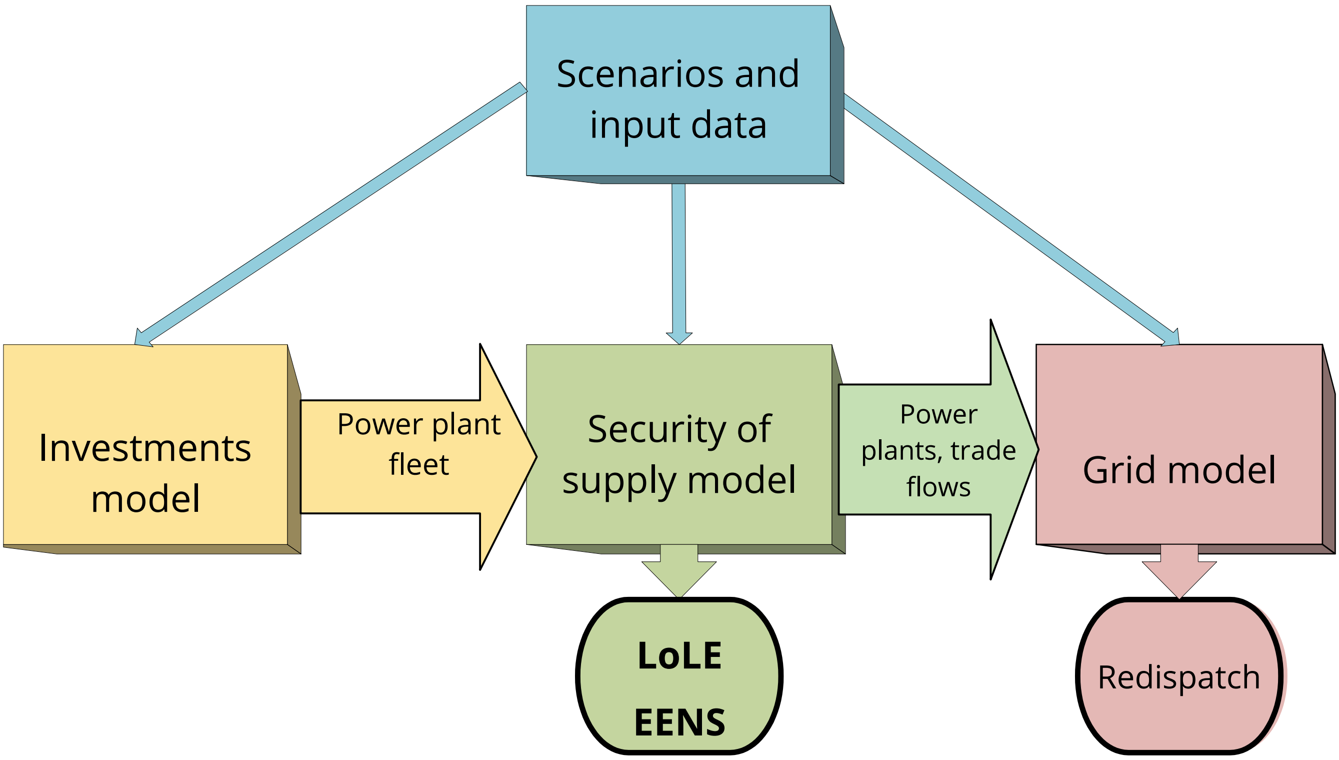
With regard to grid and system adequacy, BNetzA investigates whether the existing or the planned power grid can accommodate the electricity flows as provided through the market model analysis. In addition, the volume of the necessary redispatch should also be calculated.[87] The term "redispatch" refers to the practice of German TSOs to use technical changes in the dispatch schedule resulting from market outcomes to avoid congestion in the transmission grid. After calculating potential congestion after markets have closed, the TSO orders electricity plants to ramp generation up or down, depending on their location in the grid. These changes are remunerated based on administrative rules and are financed via grid fees. They have no impact on the market transaction—i.e. effective delivery and remuneration are in line with the original market result.

Reflecting the slow speed of transmission expansion, redispatch has become considerably more significant over the past years. Compensation today amounts to several hundred million euros. While any generation asset may be obliged to participate in redispatch, the German regulator has established a grid reserve (***"Netzreserve"***) to ensure that sufficient generation capacity is available for redispatch. For obvious reasons, the location of these plants is crucial—most of them are located in southern Germany near industrial load centres.

The model consists of three sub-models: an investments model, a security of supply model and a grid model (see Figure 7 below). The investments model provides an overall framework for the analysis. It assumes profit maximisation as the market participants' main premise.[88]

The procedure applied by BNetzA in monitoring the security of supply is presented in Figure 7 below.

Figure 7. Overview of the procedure applied by BNetzA in monitoring the security of supply



Source: Bundesnetzagentur, PowerPoint presentation during the "Monitoring of security of supply" stakeholder meeting organised by Bundesnetzagentur on 16 March 2021[89] (own English translation)

Quantitative metrics

BNetzA applies the same quantitative metrics as the VS analysis model, mainly LoLE and EENS (see subsection 2.2.3). According to BNetzA, in order to draw conclusions on the level of security of supply from those two metrics, a **reliability standard** must be defined:

- How high is the consumer's ability to pay for an uninterruptible electricity supply?
- When does the under-covering of load represent a risk for the security of supply?[90]

This standard, in turn, depends on consumers' willingness to pay for uninterrupted electricity consumption. According to BNetzA, this standard could be defined by the parliament, the BMWi/BMWK, or BNetzA.[91]In August 2021, the BNetzA, jointly with the Luxembourg Ministry of Energy and Spatial Planning, determined a LoLE value of 2,77 hours per year as a new reliability standard for the German-Luxemburg bidding zone[92] (see also footnote 2 in the subsection 2.2.3). This corresponds to a LoLP of 0,04%.

Quantitative value of different generation sources and other assumptions

Similar to the ENTSO-E methodology (2014), the Consentec and r2b methodology (2015) as well as the VS analysis model (2019), BNetzA does not assign any specific capacity values to the individual technologies. BNetzA explained its reasoning in a written response to dena:

"First of all, it must be stated that the Federal Network Agency does not plan any generation capacities, but rather observes, calculates and evaluates future developments and prepares a report on it. With these calculations, each technology can contribute to meeting the demand for electricity within the framework of system cost minimisation. For these calculations, assumptions are made about the future expansion of RE and the share of renewable electricity in gross electricity consumption. In addition, political decisions on the coal and nuclear phase-out play a role, as do the market-driven expansion and shutdown of other conventional power plants and storage facilities. This means that the further expansion or dismantling of power plants results from model calculations. The feed-in from RE is mapped using historical feed-in time series or weather data, which are scaled based on the installed capacity (forecast errors are included). The feed-in of RE is modelled as a function of the supply and is accordingly assumed to be inflexible. In contrast, conventional power plants and storage facilities can freely participate in the electricity market; their provision of power is only restricted by planned and unplanned unavailability. This is also reflected in the modelling."[93]

2.2.5 Determination of the extent of the German capacity reserve

The capacity reserve *(Kapazitätsreserve*) was introduced in 2016 by the Electricity Market Law *(Gesetz zur Weiterentwicklung des Strommarktes*, or also *Strommarktgesetz)*. It is an additional component of the market design, although the capacity reserve is settled outside the electricity market. The reserve should provide additional capacity when there is insufficient supply available on the wholesale or control energy market to meet the entire demand. The German TSOs purchase the necessary capacities through competitive public tenders. These tenders determine which facilities will establish the reserve in the future delivery period. Closed coal plants scheduled for retirement, gas power plants and energy storage facilities (if not selling electricity on the market), as well as RE (if not selling electricity on the market), can participate in the tenders and enter into the capacity reserve. The TSOs give those facilities annual compensation payments for remaining in standby as long as the TSOs do not need to activate them. The TSOs pass the costs on to the end users in grid fees.[94] Apart from the capacity reserve procured by a tender process, a second type of reserve was formed from retired lignite fired power plants (***"Sicherheitsreserve"*** or safety reserve) based on administrative remuneration.

In 2018, the European Commission approved Germany's capacity reserve as compliant with EU rules on state aid.[95] The reserve was capped at 2 GW for the period from 2019 to 2025,[96] which is less than 1% of Germany's 2020 total electric generation capacity of just over 226.8 GW.[97] The first delivery period started on 1 October 2020 and will end on 30 September 2022.

The extent of the capacity reserve was determined by the BMWi based on the so-called *reasonable worst case scenario*. The analysis of this scenario led to the conclusion that the capacity reserve should have a volume of 2 GW to cover the electricity market demand in extreme situations or to reduce any shortfalls to an acceptable level.[98] The results of the 2019 VS analysis show that employing the capacity reserve leads to further reducing the LoLP in Germany, both in the reference and in the ambitious scenario. However, the LoLP is already very low even without using the capacity reserve.[99] Furthermore, the capacity reserve has not yet been used.[100]

In the first and only tender so far, the successful bids encompassed only 1.056 GW, and the remaining bids failed to qualify.[101] The current capacity reserve consists only of gas-fired power plants. This also confirms that Germany's power supply remains ample. However, as stated above, BNetzA's future analysis may arrive at slightly different results, as it will be based on different scenario assumptions derived from the updated policy targets and measures.

3 Methods for quantifying grid and system adequacy: The methodology of the German Grid Development Plan (NEP)

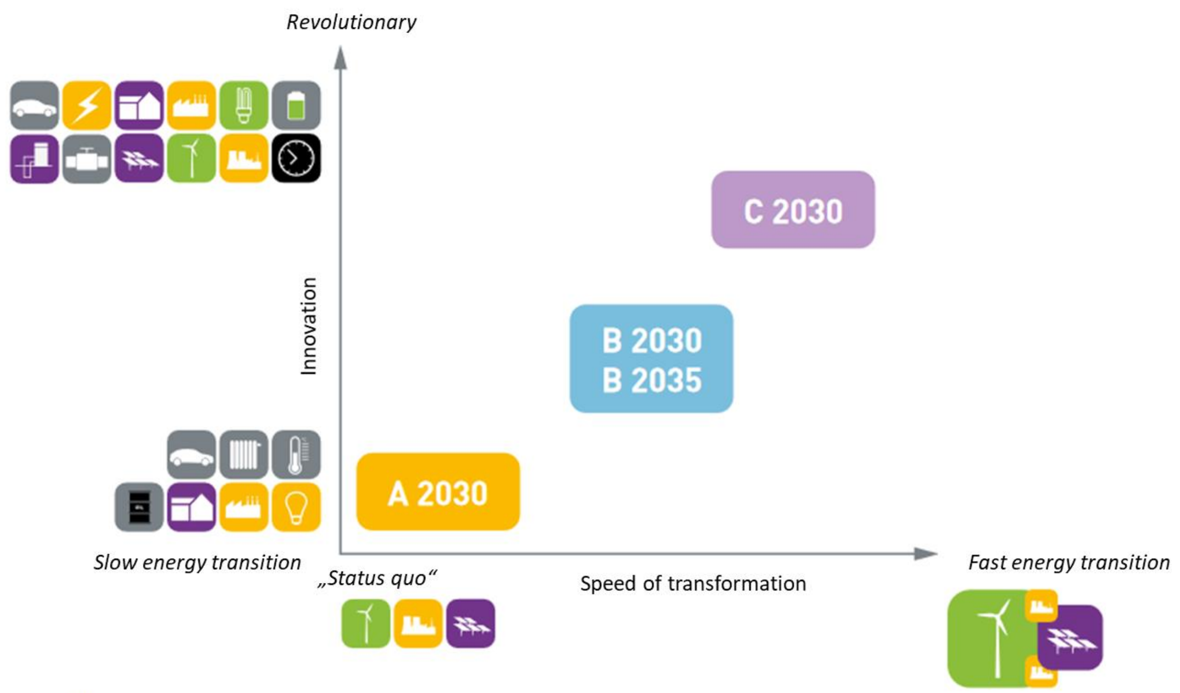
3.1 Background on process and responsibilities

Germany's grid development is set out in the Grid Development Plan for Electricity (*Netzentwicklungsplan Strom*, or NEP), which is published bi-annually. The German TSOs coordinate the compilation of the plan, which is then reviewed in a stakeholder process and finally approved by the regulator. Section 12 of the EnWG mandates that the TSOs and regulators conduct this process every two years.

The NEP specifies the grid reinforcements and additions necessary in the short and medium term (3–20 years) based on three main generation development scenarios presented in the so-called scenario frameworks, which are separate publications. These comprise a Business-as-Usual scenario (Scenario A), a Realistically Ambitious scenario (Scenario B), and a Fast Development scenario (Scenario C). As its name implies, Scenario B is typically considered the most realistic lead scenario. It has timeframes of 15 and 20 years, while the other scenarios have timeframes of 15 years (formerly 10 years).

The scenarios are developed by the TSOs and must be approved by the regulator before they can be used in the grid planning process (NEP). The scenario scope has changed slightly over the years. Past iterations focused on the speed of the transition and the level of innovation (Figure 7). However, the latest version has added **sector coupling and electrification,** as well as a **focus on the grid** as parameters (8). The focus on the grid metric describes measures undertaken on the side of generation and load to avoid grid congestion and the need for grid reinforcements, such as grid-oriented regionalisation of new generation capacities and the introduction of enabling measures such as grid storage and electrolysers.

Figure 8. Scenario classification for the NEP 2030 (2016), own translation



Source: Übertragungsnetzbetreiber (2016).[102]

Figure 9. Scenario classification for the NEP 2035 (2020), own translation

Source: Übertragungsnetzbetreiber (2020).[103]

3.2 Capacity adequacy in the NEP

Capacity adequacy itself is explicitly not considered in the NEP. However, the NEP relates explicitly to the capacity adequacy assessments prepared by the TSOs and the ENTSO-E (see sections 2.2.1 and 2.2.2) as external studies not within the NEP scope.[104] As stated in the NEP 2035, the NEP is not intended to assess the overall security of supply but rather to develop a plan based on pre-defined scenarios that ensure that the grid does not present a barrier to the security of supply, RE development and climate policy goals.

The market and grid modelling conducted for the development of the NEP contain additional slack generators outside of the scenario framework to ensure that the system is always adequate on the supply side and that **shortages of conventional generation capacity do not act as drivers of grid development.** This is related to the fact that the underlying optimisation algorithm has the hard constraint that the load must always be covered. A single situation in which generation capacity is inadequate could trigger large grid investments in the model, which is avoided by using the slack generators, which essentially represent "energy not served", without explicitly allowing the occurrence of that parameter in the model. The latest iteration of the plan, NEP 2035, states that none of these slack generators were actually generating in any of the final simulation cases on which the plan is based. This can be considered as an indicator of capacity adequacy in all scenario frameworks.[105]

4 Comparison of the methodologies used in Germany

This chapter presents a summary comparison of the most important features of each described methodology in the form of a table.

Table 1. Summary comparison of the methodologies in the German power system assessment

Characteristics of the methodology/ Methodology	TSOs' methodology to estimate national power balance	ENTSO-E adequacy assessment methodology	BMWi transnational assessment of capacity adequacy (2015)	BMWi VS analysis model (2019–2021)	BNetzA monitoring of security of supply since 2021
Other methodologies on which the model is based			ENSO-E adequacy assessment methodology	BMWi transnational assessment of capacity adequacy (2015)	BMWi VS analysis model (2019–2021)
Goal/Research scope	Determine the remaining capacity at defined points of time in the past and future	Determine the probability of load balancing in a number of interconnected areas with limited transmission capacities in the EU	Determine the probability of load balancing within the considered geographical scope	Assess whether the security of supply can be maintained efficiently in the European power system	Assess the security of supply both in relation to the power market (capacity adequacy) and the power grid (grid and system adequacy) based on the defined reliability standard
Approach	Deterministic approach with stochastic elements such as peak loads, unplanned outages and weather-dependent outages	Combined deterministic and probabilistic approaches (deterministic forecasts + uncertain factors such as temperature, RE generation and forced outages)	Probabilistic and cross-border approach that accounts for the stochastic characteristics of system elements as well as the impact of the cross-border power exchange and transmission restrictions	Probabilistic and cross-border approach that accounts for the stochastic characteristics of system elements as well as the impact of the cross-border power exchange and transmission restrictions	Probabilistic and cross-border approach that accounts for the stochastic characteristics of system elements as well as the impact of the cross-border power exchange and transmission restrictions
Procedure	Compares a real reference situation with a theoretical scenario characterised by critical parameters at a defined point in time	Optimisation procedure using Monte Carlo simulations of different climate conditions and random forced outages for a given target year	Optimisation procedure to obtain stochastic and time-coupled simulation years	Optimisation procedure to obtain stochastic and time-coupled simulation years	Modelling includes three steps: investments model, security of supply model and grid model
Investigated point in time	One defined hour in a year	Hourly simulation	Hourly simulation	Hourly simulation	Hourly simulation
Data set	Available forecasts and historical data for load, generation and outages	Available historical data for load, generation and outages	Available historical (2010, 2011, 2012) weather data for generation from RE and pumped-storage systems, load data as well as typical outage	Available historical (2009, 2010, 2011, 2012, 2013) weather data for generation from RE, load data, data on extension potential for RE, data on seasonal changes in the water	Available historical data such as for generation, load, heat demand, DSM potential, storage capacities and cross-border interconnection capacities; in the case of RE,

			rates for conventional power plants	flow in rivers, feed-in values and full-load hours for geothermal plants, bioenergy plants, landfill, sewage and pit gas, as well as typical outage rates for conventional power plants	historical feed-in time series or weather data are scaled based on the installed capacity
Dealing with uncertainty	2 scenarios: with and without coal-phase out	Monte Carlo samplings	999 different simulations/scenarios	Reference scenario (best guess scenario without any additional climate protection measures) and alternative scenarios; 1,750 different simulations (year scenarios) for each scenario	"Best guess" basis/reference scenario: the most probable development resulting from fulfilling the current energy policy goals
Quantitative metrics	- Reliable available capacity - Peak load - DSM - Remaining capacity	- LoLE - LoLP - LBP - EENS/LoEE -	- LBP for each forecast year and country considered	- LoLE - LoLP - EENS/LoEE - SAIDI - Power Market SAIDI - Contribution of imports to ensure the security of supply	- LoLE - EENS
Quantitative value of different generation sources	No specific capacity value	No specific capacity value	No specific capacity value	No specific capacity value	No specific capacity value
Other assumptions	Biomass and biogas power plants available for at least 99% of the time Conventional power plants: unscheduled outages occur at annual peak times; the cumulative probability of outages amounts to 95%		Biomass: only inflexible generation is considered	Market participants behave in line with rational expectations Cross-border power exchange takes place only if it is no longer possible to meet the demand with own generation units within a bidding zone or a country	Reliability standard: LoLE of 2,77 hours per year, which corresponds to a LoLP of 0.04% Market participants trade to maximise their profits
Geographical focus	German electricity system and all units technically assigned to it	EU	Germany and its geographical and electric neighbours	Core region: Germany, its neighbouring countries, Italy, Great Britain and Scandinavian countries;	Germany and the neighbouring electricity markets – in particular, the German-Luxembourgish bidding zone

				Modelled satellite region: Iberian Peninsula	
Effects of the European internal market	Not considered	Considered by taking into account cross-border power exchange (import/export)	Considered by taking into account cross-border power exchange (import/export)	Considered by taking into account cross-border power exchange (import/export) between the countries of the core region, as well as between the countries of the core region and the modelled satellite region	Considered by taking into account cross-border power exchange (import/export)
Time frame	The previous, current and the next couple of years	10 years Two target years	10 years Three target years	10 years Four target years	10 years
Time period of the recent analysis	Review of the year 2018 Forecast for 2019–2022	2020–2030 Target years: 2025 and 2030	2015–2025 Target years: 2015, 2020 and 2025	2020–2030 Target years: 2020, 2023, 2025, 2030	Not yet available
Strengths and weaknesses	**Weaknesses:** - considers only the most probable situations in the power system - does not consider cross-border power exchange - does not consider grid adequacy	**Weakness:** elements of the deterministic approach **Strengths:** - considers cross-border power exchange - considers grid adequacy	**Strengths:** - probabilistic approach - considers cross-border power exchange **Weakness:** does not consider grid adequacy, only cross-border transmission capacities	**Strengths:** - probabilistic approach - considers cross-border power exchange **Weakness:** does not consider grid adequacy, only cross-border transmission capacities	**Strengths**: - probabilistic approach - considers both cross-border power exchange and grid adequacy

Source: Own representation. Similarities are marked in green.

5 Emerging developments in German power system assessment

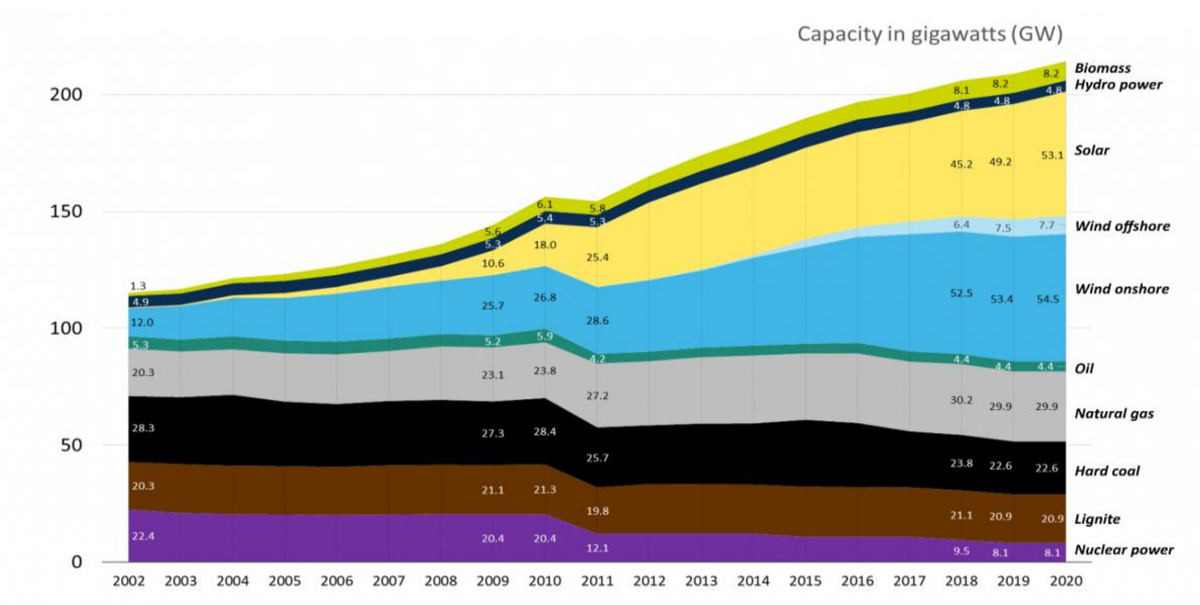
5.1 Expected changes due to phase-out of coal and nuclear power

Germany is currently in the process of phasing out both nuclear and coal power, reducing nuclear capacity from 22 GW in 2000 to zero by the end of 2022 and coal capacity from 44 GW in 2020 to zero by the end of 2038.[3]

A public discussion about generation adequacy started as early as 1998 when the newly elected German government announced that it would go through with the nuclear phase-out it had promised during the election campaign. The nuclear exit was signed into law in 2000, revised in 2010 after a government change, revised again in 2011 after the Fukushima incident in Japan and has proceeded since 2011 without any reduction in security of supply. As of late 2021, 8 GW of nuclear capacity remains online, all scheduled to retire by the end of 2022. So far, the fear that Germany could become a net power importer dependent on nuclear and coal capacities in neighbouring countries has failed to materialise. This is partly due to the rapid development of RE but also to the fact that the German system still had some overcapacity.

Nevertheless, capacity adequacy has become a concern for German TSOs and the regulator. Concerns were exacerbated by the combination of high natural gas prices and cheap domestic coal, as well as an increasing RE share that made a large share of the German CCGT (combined cycle gas turbine) fleet increasingly uneconomical to operate in the early 2010s. While modern CCGT units are highly efficient and flexible—albeit usually not both at the same time—and would, in theory, be optimal partners for increasing variable RE generation, many gas plants were displaced from the market because the merit order favoured the cheap baseload generation from coal and the priority-dispatched RE. This trend has reversed somewhat in recent years as increased CO_2 prices under the European Union Emissions Trading System (ETS) have made coal less competitive. However, a large-scale decommissioning of conventional capacities beyond the nuclear phase-out has yet to happen, as the following graph representing German generation capacity illustrates:

Figure 10. Development of generation capacity in Germany 2002–2020



Source: Appun 2021[106].

[3] As of early 2022, the coal exit has been shifted forward to 2030; however, the impact of the ongoing Russia-Ukraine crisis, which impacts the natural gas supply to Germany, is unclear at this point.

Since 2011, only around 3 GW of hard coal capacity has been decommissioned. Lignite capacity has even increased by 1 GW. This development has been favoured to some extent by regulatory intervention through establishing different cold reserves of gas and coal power plants. German TSOs, with regulatory approval, remunerate some generation capacity to remain available as a cold reserve that can be dispatched either day-ahead or with a lead time of a few days. There are three different types of cold reserve:[107]

1. ***Netzreserve* (grid reserve):** Currently gas and coal power plants, especially in southern Germany, where most of the nuclear capacity was located and little wind power is available, which are available for re-dispatch to relieve grid congestion (see explanation in subsection 2.4.4)
2. ***Kapazitätsreserve* (capacity reserve):** Currently mainly gas power plants that can be activated within a few hours if there is a capacity shortage in the market (currently 2 GW of capacity) (see explanation in subsection 2.2.5)
3. ***Sicherheitsbereitschaft* (safety reserve**): Mothballed coal power plants available for reactivation within a few days (this scheme is scheduled to run out in 2023) (see explanation in subsection 2.2.5)

All of these reserve power plants are not allowed to participate in the market; instead, TSOs pay their costs, which are recovered through grid fees. Furthermore, the TSOs and BNetzA have declared many power plants in southern Germany, mostly CCGT units, system relevant, which means that these plants may not be decommissioned in the foreseeable future. This shows that capacity adequacy is already a concern for the German power system and has been for several years, although the security of supply has not yet been endangered. The capacity and security reserves have never been used, only the grid reserve.[108]

The impending coal phase-out will certainly exacerbate these capacity adequacy concerns in Germany. Legislation initiating the decommissioning of all coal power plants by the end of 2038 was passed in 2020 and moved forward to 2030 by the government elected in late 2021.

For at least a decade, power sector officials have debated the general implications of the coming reduction in Germany's conventional generation capacity. This debate has even catalysed discussion about pan-European capacity adequacy. European capacity adequacy is especially relevant as several countries in Europe plan to retire coal capacity. Moreover, nuclear power plants in different countries are approaching the end of their technical lifetimes.

In the interconnected European system with increasing market integration, it is no longer possible to approach and perceive generation adequacy at the level of a single country. Therefore, ENTSO-E and its predecessor UCTE (Union for the Coordination of the Transmission of Electricity) have assessed capacity adequacy Europe-wide. ENTSO-E explicitly mentions the reduction in European coal and nuclear capacities as one of the drivers behind building on its Mid-Term Adequacy Forecast (MAF) to develop the European Resource Adequacy Assessment (ERAA) methodology, which should be applied now and in all future assessments.[109]

The ERAA methodology is a leap forward from the MAF, taking into account additional parameters that impact capacity adequacy, such as the European flow-based market coupling (FBMC) mechanism.[4] It also takes into account technologies such as batteries and power-to-X to a greater degree. In this regard, the ERAA is exemplary for the changes required in capacity adequacy assessment methodology in Germany and elsewhere in the future. In the case of Germany, these changes are not primarily driven by the nuclear and coal phase-out. Other factors that need to be taken into account include:

- **Generation location and grid capacity:** A country or a control area may have an adequate supply in theory, but if the grid is incapable of transporting power to the load centres, it may be incapable of covering all demand. As the best places to locate RE generation are typically far from load centres, the retirement of former baseload generation units located close to load centres increases the importance of the grid in the capacity adequacy assessments.
- **Interconnections, electricity trading and resource sharing:** A country or a control area that cannot cover its load with domestic resources may still have adequate supply if the power can be reliably imported/exchanged. Moreover, the capacity contribution of RE resources increases with interconnection and resource sharing. Correct assessment of these characteristics requires a coordinated pan-European approach, as the effects may be under- or overestimated by national planners. For example, in 2018, the German Association of Energy and Water Industries (BDEW) published a study showing that the TSOs and BNetzA overestimated the available capacity in neighbouring countries.[110]

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[4] **Flow-based market coupling** is used to maximise the usable transfer capacities between bidding zones. It differs from the previously used net transfer capacity (NTC) approach mainly in the fact that transfer capacities are continuously adjusted based on load flow calculations and the status of the grid. NTCs were also based on load flows, but bilaterally agreed between TSOs on a yearly or half yearly basis with fairy large security margins.

- **Flexibility measures**, such as DSM, energy storage and power-to-X.

Concerning the coal phase-out, both the methodology of capacity adequacy assessment and the measures to be taken in the event capacity is not adequate are relevant. Subsidising system relevant plants to remain online may be an appropriate measure to prevent a large scale CCGT decommissioning in the short term, but not in the case of the large coal capacities retiring in the course of the coal phase-out. Such a measure would contradict climate policy goals and the coal exit strategy. The introduction of a capacity market to incentivise the construction of new cleaner and more flexible CCGT plants has been discussed in Germany for years; as of today, it is unlikely to be introduced. German TSOs are currently working on a strategy for the coal phase-out, and further publications on the issue can be expected starting in 2022. These publications and further assessments on capacity adequacy are likely to renew the discussion over capacity markets in Germany. The new coalition agreement foresees a commission (*Plattform klimaneutrales Stromsystem* – "Platform Climate Neutral Power System") to study these questions, among other things.

5.2 Are there other possible or necessary changes?

The capability of the German system to cover the load at all times is linked to grid capacity and grid congestion. **Adequate dispatchable generation capacity and/or import capacities are obviously necessary but not sufficient for the security of supply**. This was already clear when the grid reserve was under discussion starting in 2013 (with real world introduction in 2016). Unlike the capacity and security reserves, the grid reserve is frequently used to alleviate grid congestion between North and South Germany. While there is enough generation capacity available at all times, the shift towards wind generation in Northern Germany and the decommissioning of conventional generation close to the load centres in Southern Germany have increased the magnitude and importance of North-South power transmission. To address this issue, the German government introduced the NEP, first published in 2013. Grid expansion has progressed much more slowly than anticipated, not least due to the cost considerations and public acceptance issues. McKinsey stated in its annual energy transition review in 2019 that if grid expansion was not significantly accelerated, the targets for 2020 set out in the first NEP would not be reached until 2037.[111] Grid adequacy is currently as challenging for the security of supply as capacity adequacy – although the latter is only relevant due to the coal phase-out decided in 2020. Grid adequacy will become even more important due to the coal phase-out, since RE will replace most of the coal contribution to electricity production.

In this regard, it is surprising that the NEP continues to explicitly state that capacity adequacy is not within its scope. In our view, **capacity adequacy and grid adequacy in Germany are inextricably linked, and the planning and assessment approaches should reflect this**. It is probable that this is happening already behind the scenes, since the TSOs in charge of the NEP also prepare their own capacity adequacy assessments, which BMWi/BMWK and BNetzA in turn include in their own capacity assessments. It is also probable that the TSOs link both processes and assessments internally. However, the process would benefit from more transparency. The coal phase-out will lead to more interlinking of the capacity and grid adequacy assessments in Germany. The shift from the MAF to the ERAA methodology by the ENTSO-E shows that this interlinking is already taking place at the European level. It will undoubtedly impact the processes and methods applied in Germany.

6 Conclusions and relevance for China

German and European capacity adequacy studies have undergone significant changes over the past decade to reflect the scale-up of RE and the increasing interaction between probabilistic events such as weather, demand spikes and plant outages. More changes are likely as sector coupling, electrification of transport and other sectors, and interconnector capacities grow in importance.

Main findings

In this study, we have illustrated and provided technical detail concerning the evolution and current grid planning practices and capacity adequacy studies at German TSOs, the relevant ministries and grid authorities and ENTSO-E. Our main conclusions are:

- Grid planning has increased in importance over time, and responsibility for undertaking such planning lies with the TSOs. The responsibility for the capacity adequacy assessment currently lies with BNetzA. Since responsibility for grid planning and capacity adequacy remain siloed in many respects, addressing this deficiency would help improve the efficiency and effectiveness of planning and power system assessment overall.
- Similarly, efforts to model and assess capacity adequacy have expanded in geographical scope as well as in how far forward they look. This trend will likely become more evident as the need to consider pan-European capacity adequacy grows due to phasing out coal and retiring nuclear in many regions.
- Capacity adequacy models have shifted from deterministic approaches towards more probabilistic models that consider the interaction of multiple scenarios of weather, plant and transmission outages and demand spikes. Not only does this reflect the rising importance of variable RE, but it also reflects the increasing interaction of improbable events for causing short-term power shortages.
- Current models do not specify a capacity value (such as effective load carrying capacity or ELCC) for each generation source. Instead, the models assume each type of generation will have a part to play, with conventional generation gradually phasing out due to policy targets and carbon prices.
- So far, existing models make inadequate consideration of sector coupling and demand-side flexibility. These are presently a minor factor in European power demand but could grow rapidly, especially as electric vehicle adoption accelerates and vehicle-to-grid technology becomes commercially viable.
- All capacity adequacy models currently in use suggest that Germany's power sector remains well-supplied for the coming years, in part due to overcapacity in Germany and its neighbouring countries, but also due to the flexibility of the conventional power plant fleet as well as the existence of efficient energy markets and interconnections with neighbouring regions.
- Germany's capacity reserve is unlikely to be used in the next couple of years due to ample capacity in Germany and its neighbouring regions—although the new German climate policy targets and the Russia-Ukraine crisis may change the situation. In any case, capacity markets remain a hot topic across Europe, including in Germany.

China's power system planning model

In 1997, China adopted the *Principles of Power Development Planning*. These principles clarify that the power planning schedule is consistent with the national economic development plan and divided into short-term plans (5 years), medium-term plans (10–15 years), and long-term plans (15 years or more). Both the short-term and long-term plans are revised every five years, and the medium-term planning is revised every three years.[112]

China's power system planning is divided into national (including regional) power planning and provincial power planning. In 2016, the National Energy Administration (NEA) issued the *Measures for the Management of Electric Power Planning*, which clarified the participants and corresponding responsibilities of the two types of power planning.[113] The national power plan is led by NEA, and the provincial power plan is led by the provincial energy authorities. NEA's plan is ultimately reviewed and approved by the National Development and Reform Commission (NDRC), while provincial plans are harmonised with the national plan.

Load forecasting is the first step in power planning. China employs a bottom-up approach, from the province level to the regional level to the national level, focusing on long-term electricity demand, peak load, load distribution and load structure.[114] The load forecast only includes three scenarios: high, medium, and low growth. The high-growth scenario mainly reflects strong economic growth and the load in continuous high-temperature weather in the summer. The medium-growth scenario represents the steady operation of the economy and the slow temperature rise in the summer. The low-growth scenario considers slowed economic growth and summer temperatures lower than the normal level.[115] Ultimately, only one load scenario will be recommended as the basis for subsequent power generation planning and grid planning.

Generation capacity planning determines the amount and location of each power source. The process will evaluate multiple power source construction plans to determine the new capacity required and investment needs.[116] Based on the policy goals of non-fossil energy share and provincial RE quotas, power generation planning will first develop scenarios for non-fossil power sources.[117] In each scenario, according to the regional power balance and local renewable power consumption capability, the plan proposes the amount of each region's fossil power capacity and peaking capacity. Finally, the regional total installed capacity and power structure will be determined according to an economic and technical analysis.[118] The scenarios will consider different resource conditions and policies as well as regional characteristics, using annual, monthly or typical weekly and daily load curves.[119]

Current issues in China power system planning

There is relatively less transparency in China surrounding capacity adequacy planning in general, but grid planners are well aware of many of the techniques discussed in this report, particularly the key metric of LoLP. China has made significant strides in recent years in developing domestic electricity markets, including spot power market pilots and markets for ancillary services.

However, China's electricity market differs from Germany in several major respects related to planning for capacity adequacy. First, spot markets are a relatively recent development. They likely have not yet reached the volume and liquidity necessary to play a similar role in ensuring capacity adequacy to those in Europe. Power prices are still relatively fixed—although price caps for coal power have been raised recently and may have no upper cap in the case of certain energy-intensive industries—and this affects whether generators or users have adequate incentive to ensure supply or flexibility, particularly at times of peak demand. As a result, administrative planning plays a predominant role relative to market forces.

Barriers to inter-provincial power trading have also played a notable role in the discussion of capacity adequacy, and provinces have often sought to ensure peak load can be met primarily through dispatchable coal or other baseload resources, including dedicated imports via high-voltage power lines. Power system planning explicitly accounts for the addition of new renewable resources and targets (both provincial and national) for non-fossil energy. However, renewable resources may currently receive little or no value in provincial planning to meet peak loads. Recent analysis has shown that greater inter-provincial power trading and reserve sharing could substantially reduce costs and scale down the requirement for fossil generation to back up renewables as the country moves towards its carbon peaking and carbon neutrality goals.[120]

While China's power market and power system structure differ radically from those of Germany and Europe, some broad trends in Europe point to potential future directions in China's power sector planning. First, the move away from deterministic planning models towards increasingly complex probabilistic approaches—in which various probability supply and demand scenarios interact—may alleviate some concern about the low peak load capacity value of variable renewables and lead to more efficient planning for new transmission and generation investments. Second, the trend in Europe to move away from TSO-specific or country-specific capacity adequacy planning towards regional capacity adequacy planning would draw more attention to the need for increased trading between provinces and greater consideration of the mutual complementarity of renewables and flexible demand resources when considered over a broader geographical area.

Concluding remarks

Ultimately, the development of a power system with clean RE at its centre is a work in progress, and no region has fully adapted its assessment or planning methodologies to fully incorporate emerging resources such as the flexible charging of electric vehicles or the electrification of heating and industry. The measures already adopted in Europe and Germany to ensure capacity adequacy are themselves a work in progress. By sharing lessons and experiences with China and other countries engaged in a long-term transition to low-carbon energy systems, we can test and improve existing models and methodologies to ensure power systems remain reliable as we progress towards a clean, low-carbon energy future.

Interview partners and participation in conferences, stakeholder meetings etc.

Interviews, questions or email correspondence

Renewables Grid Initiative, interview on 9 February 2021.

50Hertz Transmission GmbH, written responses on 17 February 2021 and 16 March 2022.

Venios GmbH, interview on 17 February 2021.

Bundesnetzagentur, written responses on 16. March 2021, 20 January 2022 and 17 March 2022

E.DIS Netz GmbH, interview on 17 March 2021.

Meetings

"Monitoring of security of supply" stakeholder meeting, organised by Bundesnetzagentur on 16 March 2021.

Abbreviations

BDEW – *Bundesverband der Energie- und Wasserwirtschaft e.V.* (German Association of Energy and Water Industries)

BMWi – *Bundesministerium für Wirtschaft und Energie* (Federal Ministry for Economic Affairs and Energy)

BMWK – *Bundesministerium für Wirtschaft und Klimashutz* (Federal Ministry for Economic Affairs and Climate Action)

BNetzA – *Bundesnetzagentur* (Federal Network Agency)

CCGT – combined cycle gas turbine

CHP – combined heat and power

DSM – demand side management

EENS – Expected energy not served

ENTSO-E – European Network of Transmission System Operators for Electricity

EnWG – *Energiewirtschaftsgesetz* (Energy Industry Act)

ERAA – European Resource Adequacy Assessment

EU ETS – European Union Emissions Trading System

EU – European Union

FMBC – flow-based market coupling

LBP – Load Balancing Probability

LoEE – Loss of energy expectation

LoLE – Loss of load expectation

LoLP – Loss of load probability

MAF – Mid-term Adequacy Forecast

MC samplings/simulation – Monte Caro samplings/simulation

NEA – National Energy Administration

NDRC – National Development and Reform Commission

NEP – *Netzentwicklungsplan* (Grid Development Plan)

NTC – net transfer capacity

RE – renewable energy

TSO – Transmission System Operator

TWh – terawatt hours

UCTE – Union for the Coordination of the Transmission of Electricity

VS – *Versorgungssicherheit* (security of supply)

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Endnotes

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