System Adequacy for Germany and its Neighbouring Countries: Transnational Monitoring and Assessment

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The results described in this study are based on the investigations and analyses conducted by Consentec GmbH and r2b energy consulting GmbH within the scope of the project:

(in German: Erneuerbare Energie als Leitlinie für das Marktdesign der Zukunft
Untersuchung zu Leistungsfähigkeit und Weiterentwicklungsoptionen der Strommärkte für die effektive und effiziente Integration erneuerbarer Energien („**Leitstudie Strommarkt**"))

This project is a joint research project of r2b energy consulting GmbH, Connect Energy Economics GmbH, Consentec GmbH and the Fraunhofer Institute for Systems and Innovation Research ISI commissioned by the Federal Ministry for Economic Affairs and Energy (BMWi).

Consentec and r2b energy consulting are exclusively responsible for this final report. All described valuations and assessments do not necessarily comply with the BMWi's or other partners' valuations and assessments.

Contents

Abbreviations

BMWi	Federal Ministry for Economic Affairs and Energy
DSM	Demand Side Management
RES	Renewable Energy Sources
LBP	Load Balancing Probability
LOLE	Loss of Load Expectation
PV	Photovoltaic
SOAF	System Outlook and Adequacy Forecast
TSO	Transmission System Operator

Abstract

System adequacy in Germany can only be considered and assessed in a transnational perspective as the German electricity grid is closely interconnected with the power systems of the neighbouring countries. Furthermore, electricity is traded cross-border and considerable portfolio effects exist in the European interconnected system. Hence, for the monitoring and assessment process of generation adequacy, an appropriate calculation method is necessary, which in particular copes with the effects of cross-border exchange.

All involved countries benefit from cross-border electricity exchange: particularly, portfolio effects with respect to production from renewable energy sources (RES), load and availability of power plants have the effect that system adequacy can be achieved at lower costs and thus more efficiently. To use such portfolio effects belongs to the most important objectives of the European internal market for electricity. In practice, such portfolio effects of course can be used to the extent cross-border transmission capacities are available.

In the region covering Germany and the neighbouring countries connected electrically and/or geographically, load and generation are balanced at any time with an extremely high probability of almost 100% up to the year 2025. This core result is based on the “best estimate” scenario of the ENTSO-E on the development of load and generation. The analysis explicitly considers the portfolio effects between Germany and its neighbouring countries with respect to RES production, load and power plant availability, but also technical limitations of cross-border exchange.

Executive summary

An intensive debate on the future electricity market design can be observed in several European countries. This debate is based on the question whether the system adequacy, i. e. the possibility to balance supply and demand – can be guaranteed by the present market design in a sufficient manner, or whether fundamental adaptations of the market design become necessary.

While these issues have first been debated at a national level only with national perspective, the European dimension has become increasingly important in the recent past. This is more than necessary, in particular with a view to the target of completing the European internal market for electricity.

System adequacy in Germany can only be considered and assessed in a transnational perspective as the German electricity grid is closely interconnected with the electricity systems of the neighbouring countries. Furthermore, electricity is traded cross-border and considerable portfolio effects exist in the European interconnected system.

All countries involved benefit from cross-border electricity exchange: particularly, portfolio effects with respect to production from renewable energy sources (RES), load and availability of power plants have the benefit that system adequacy can be achieved at lower costs and thus more efficiently. The analyses we performed have shown that for a region covering Germany and the neighbouring countries connected electrically and/or geographically[1] for all weather years considered in this analysis the simultaneous residual peak load (the load, after subtracting RES-production, still to be covered by the conventional power plants) is at least 10 GW lower in 2015 and at least 20 GW lower in 2025 than the sum of the individual maximal residual peak loads of each country. In addition, portfolio effects exist for availability/outages of conventional power plants. In practice, these portfolio effects can be used – especially with respect to system adequacy – to the extent cross-border transmission capacities are available.

The relevance of inter-regional portfolio effects when assessing system adequacy will rise continuously with the Europe-wide increase of RES-production as well as the extension of interconnection capacities.

1 I.e., a region covering the following countries: Germany, Norway, Sweden, Denmark, Netherlands, Belgium, Luxembourg, France, Poland, Czech Republic, Austria, Switzerland, and Italy (because of its important role for electricity exchange in the region)

For the monitoring and assessment of system adequacy, a calculation method is necessary, which in particular considers the effects of cross-border exchange in an appropriate manner, also in scarcity situations. Such transnational approaches – also considering the increasing importance of the probabilistic character of system adequacy and the infeed of RES – have not been sufficiently established in practice. Additionally, flexibility options, especially demand response potentials and already existing emergency power systems, are to be appropriately considered in order to derive realistic statements on system adequacy.

We have developed a new method for the monitoring of system adequacy. This method calculates the load balancing probability based on a stochastic, cross-border and time-coupled (intertemporal) simulation by balancing the generation and the short-term price-inelastic share of load. First, we set up a comprehensive database of RES, infeed based on time-series from various historical weather years and used them in combination with time-series of demand for the same weather years as input data for the simulations. This is necessary to consider the stochastic behaviour of these parameters in an adequate manner.

The method proposed and the analyses should contribute to an in-depth discussion regarding the assessment of generation adequacy, a suitable monitoring method as well as the necessary input data and assumptions.

This analysis is supposed to provide a better view on the status quo of generation adequacy in Central Europe and its future development. At the same time it intends to motivate further co-operation in Europe on monitoring and assessment of generation adequacy.

In this context we have applied the new monitoring method to a specific scenario for the development of the conventional power plant fleet, of RES capacities and of the demand in Europe: this analysis is based on the ”best estimate” scenario (“scenario B”) provided by the European TSOs in the ENTSO-E System Outlook and Adequacy Forecast 2014 to 2030. The analysis explicitly considers the cross-border electricity exchange, and especially the portfolio effects for RES production, load, and power plant availability within the region considered. It shows that a load balancing probability of nearly 100% can be achieved for a region covering Germany and the neighbouring countries connected electrically and/or geographically up to the year 2025 when considering cross-border exchanges and the portfolio effects within this region. In other words: load and generation are balanced at any time with an extremely high probability up to the year 2025; this result is based on the “best estimate” scenario of the ENTSO-E on the development of load and generation, considering portfolio effects within this region and technical limitations of cross-border exchange.

These results strongly depend on the specific assumptions for the development of demand and installed generation capacities. This “best estimate” scenario of the European TSOs shows a possible development, however, not the only conceivable one. Regardless of the actual future capacity development the analysis confirms the relevance of cross-border electricity exchange (portfolio effects) and the necessity of the transnational monitoring of generation adequacy.

1 Background and motivation

An intensive debate on the future electricity market design can be observed in several European countries. This debate is based on the question whether the system adequacy, i. e. the possibility to balance supply and demand – can be guaranteed by the present market design in a sufficient manner, or whether fundamental adaptations of the market design become necessary. For that reason an adequate definition and an adequate monitoring of system adequacy is of central importance.

Necessity of a transnational approach

While these issues have first been debated at a national level, the European dimension has become increasingly important in the recent past. This is more than necessary, in particular with a view to the target of completing the European internal market for electricity.

System adequacy in Germany can only be considered and assessed in a transnational perspective as the German electricity grid is closely interconnected with the electricity systems of the neighbouring countries. Furthermore, electricity is traded cross-border and considerable portfolio effects exist in the European interconnected system.

The transformation to an electricity system more based on RES and a further growth of interconnection capacities, increases the importance of RES production, of cross-border exchange and storages as well as of Demand Side Management (DSM) for the system adequacy.

Considering the relevance of system adequacy within the current European debate and of its European dimension as well as of a significant shift of factors influencing the system adequacy, feasible methods are required to assess system adequacy. Such methods especially have to consider the cross-border electricity exchange and the probabilistic character of system adequacy in an appropriate manner. Only such a methodology of monitoring should be the basis for a profound debate about system adequacy problems on the European electricity market. The analyses in this study have focused on the development and exemplary application of such a methodology.

A transnational approach of system adequacy is not only required for an appropriate measurement of system adequacy in technical terms. The transnational electricity exchange is of use for all participating countries: Regional portfolio effects for RES, load and power plant capacities

– which the European internal market intends to develop and utilise – can achieve system adequacy at lower costs and thus more efficiently.

The European-wide growth of RES production and the continued growth of interconnection capacities will continue to increase the importance of inter-regional portfolio effects for the assessment of system adequacy, as the following figures outline:

When considering one region in Germany and its geographical and “electrical” neighbours[1], the simultaneous peak load in this region is at least 10 and up to 19 GW lower than the sum of all maximum peak loads per country in 2025. Assuming present forecasts regarding the RES growth in this region, the simultaneous residual peak load – i.e. the load after deducting RES-production still to be covered by a conventional power plant fleet[2] – is at least 20 GW and up to 27 GW lower than the sum of all maximum residual peak loads of each country in 2025.[3] Further portfolio effects occur in case of outages of conventional power plants, which are supposed to additionally reduce the demand of available generation.

Objectives

The investigations should emphasize the importance of the transnational electricity exchange based on the existing portfolio effects and the necessity of a transnational monitoring of system adequacy. Furthermore, the aim was the development and the application of a suitable monitoring method. Such a method requires to consider appropriately the portfolio effects of RES, load and power plant availabilities as well as the influence of available cross-border capacities. In particular, a specific assessment of system adequacy for a region comprising Germany and its “electrical” neighbours for a time horizon up to 2025 is to be carried out on the basis of

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1 I.e., a region covering the following countries: Germany, Norway, Sweden, Denmark, Netherlands, Belgium, Luxembourg, France, Poland, Czech Republic, Austria, Switzerland, and Italy (because of its important role for electricity exchange in the region)

2 That this demand has to be covered by conventional power plants only counts – because of a simplified approach - for the considered case of an inelastic demand. Indeed, it is – increasingly significant in the future – assumed that demand responds on market signals and therefore adjust its demand in time of scarcity , i.e. in situations if demand and available generation capacity converge in their amount.

3 In addition to the assumptions of RES growth; the actual level of portfolio effects also depends on the assumptions concerning the time-coupled RES production, load, and its correlation (cf. section 3.2, esp. section 4.1). The weather years 2010, 2011 and 2012 were considered.

(exogenous) assumptions regarding the development of load, generation capacities, and other flexibilities (DSM-potential and in a broader sense also cross-border transmission capacities).

For this purpose we have initially – based on an analysis of the current system adequacy - identified the need for action and have drafted requirements for a monitoring method which is supposed to satisfy any occurring challenge (section 2). Taking this as a basis we have developed a transnational and probabilistic assessment methodology based on a stochastic simulation. We have applied this methodology as an example for the assessment of system adequacy to a system covering a region comprising Germany and its “electrical” neighbours for a time horizon up to the year 2025. In section 3 the methodology and the main assumptions as well as the input data are reflected. The results of the certain investigations are constituted in section 4.

The results and documentation described in this study shall be the basis for an in-depth discussion regarding the assessment of system adequacy, a suitable monitoring method as well as the necessary input data and assumptions.

At the same time, it is to provide a better view on the present status quo of system adequacy in Central Europe, and on its possible development, in combination with stipulating a common approach to the monitoring method and to the assessment of system adequacy.

2 Assessment of system adequacy - status quo and need for action

2.1 Defining system adequacy with the view to this study

System adequacy combined with efficiency and environmental compatibility is an equal objective of energy policy. The term of system adequacy for the electricity supply system is differently used in various context and defined in wide terms. (cf. figure 2.1)[4]. As already mentioned in the beginning of this document, this study considers the system adequacy on the electricity market.

The term of system adequacy used in this study reflects the long-term security of power balance in the supply system, i.e. in particular the provision of sufficiently available generation capacity for a balance between supply and demand in the electricity market at anytime.

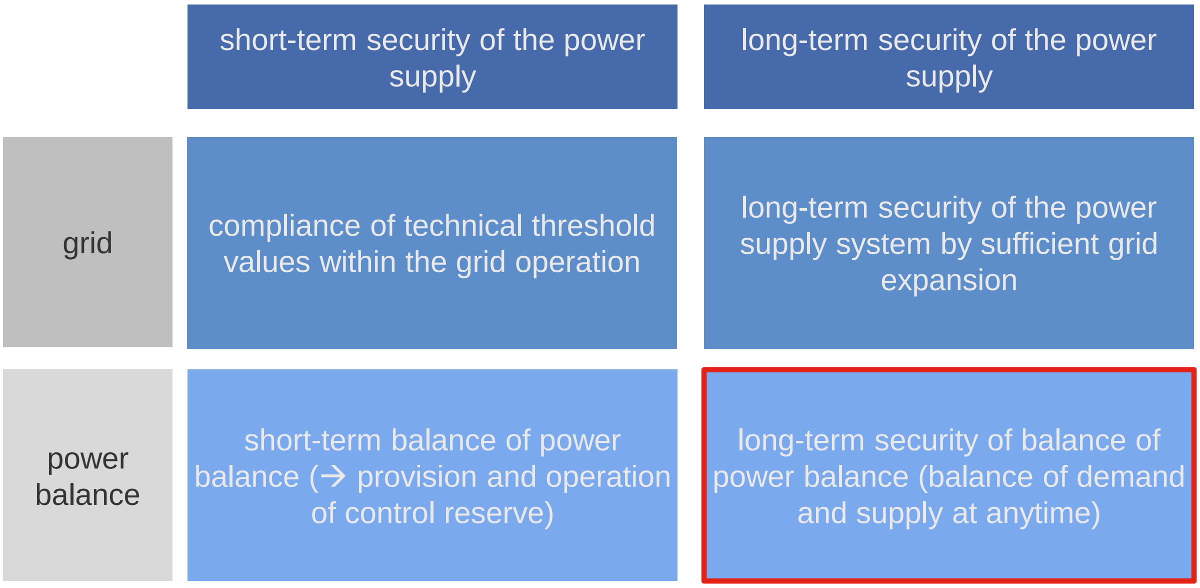

Figure 2.1 Dimensions of system adequacy in the supply system

[4] In a broader sense than explained in Figure 2.1, the term of generation adequacy could also include questions related to risks of primary energy supply.

System adequacy at the electricity market considers consumer preferences and means that those consumers can obtain electricity whose willingness to pay (benefit) exceeds the market price (costs).[5] For this reason the usable DSM has to be considered in an adequate manner.

It has to be taken into account that compulsory demand constraints would not inevitably occur if in some cases demand and supply would not be balanced on the electricity market in the future. Transmission system operators have the opportunity to take numerous measures in advance in order to prevent this situation. These measures can comprise in particular the use of control reserves as well as further available reserves, such as emergency reserves of national and international transmission system operators. Only in case that these measurements are fully exploited and the price-inelastic consumption still exceeds the available generation capacity, involuntary shutdowns of single consumers or single distribution networks (brownout) by the grid operators would be required as “last resort”. Even in such a situation a reliable operation of the European interconnected network system is still possible to avoid an extensive, area-wide power outage (blackout) [7].[6]

This study focuses on the monitoring and the parameters for assessing system adequacy, defined as the objective measuring of parameters describing the level of system adequacy. The question whether a calculated level of system adequacy can be determined as being sufficient needs to be more closely considered. Since a security level of 100 percent cannot be guaranteed from the technical point of view, the political question in this case comes down to setting the (implicit or explicit) limit parameters. Hence, the mandatory requirement of a target parameter for a certain factor of system adequacy – resp. determining whether such a requirement should be made at all – can only be realized by a political decision. This decision can be accompanied by quantitative investigations.

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5 Note that current public debates concerning system adequacy often include further factors resp. issues of acceptance. The question whether at the whole sale market electricity prices stay below the given level is sometimes mixed up with system generation adequacy.

6 An area-wide power failure resp. a large-scale grid collapse of the European transmission grid (‚Blackout‘) occurs effectively only because of disruptions of grid utilities within the transmission grid.

2.2 Status quo in respect to assessment of system adequacy

As described in section 1, debates concerning system adequacy have mainly taken place at a national level so far. Only in the recent past, the European dimension has gained importance.

In most European countries the assessment of system adequacy is currently based on mainly deterministic approaches (power balance for the point in time of the annual peak load with mainly deterministic power-plant availabilities), and on an isolated national approach. The final part of this section describes exemplarily the status quo of the procedure provided by the German Transmission System Operators (TSOs) as an example when allocating a report concerning the “power balance” (cf. [1]). Currently this report is the core element of monitoring system adequacy in Germany and has to be submitted annually according to legal requirements.

A national consideration with deterministic approaches was basically acceptable with regard to the national mainly balanced (monopole) systems in the past – based on a conventional, thermic resp. hydro-thermic generation. Under the current regulatory conditions — in particular having an international competition in the European internal market and an increased importance of intermittent RES production — such an international approach based on power balances, however, may result in a distorted assessment of system adequacy. Thus, a proper, transnational approach under consideration of a cross-border exchange on the European interconnected electricity market – compared to an improper national approach – can either increase or reduce the level of system adequacy in specific countries.

At the European level, ENTSO-E – as association of the European TSOs within the scope of the *System Outlook and Adequacy Forecast* (SOAF) – evaluates the system adequacy for all European countries. Even in this case a national assessment is made for each country, however, complemented by a simplified regional analysis. All investigations – whether national / or simplified regional – are in this case, nevertheless, analyses of single extreme situations, based on expected parameters for two “critical” hours (winter / summer peak) per year.

At the same time, ENTSO-E discusses the necessity as regard to a further developed assessment methodology, proved by the current consultation of the task force *Adequacy Assessment Methodologies* (ADAM). Within the task force the European TSOs do not propose any country specific assessment for absolute peak load situations but do evaluate a probabilistic assessment considered for the total year. Furthermore, the indicators, proposed by the TSOs (LOLE, and

ENS[7]) try to reflect the probabilistic character of system adequacy in a comprehensive manner. At the same time, (market) simulation methods are proposed to deal with cross-border interconnections. The methodology submitted by the TSOs in the PLEF picks up on an essential requirement explained in the section hereafter.

Status quo regarding monitoring of system adequacy in Germany

At this stage[1] monitoring of system adequacy in Germany is based on a national power balance which the German TSOs are legally bound to provide. The TSOs also have to produce a report for the Federal Ministry for Economic Affairs and Energy, annually to be submitted on 30 September. The report should include a review as well as a forecast. There are no further legal regulations neither for the kind of reporting nor for the method of implying the power balance. The Federal Network Agency (German: Bundesnetzagentur) has in general been authorised by legislature to fix esp. a methodology. Currently, a specific method is designed by the TSOs, in coordination with the Federal Ministry of Economic Affairs and Energy as well as the Bundesnetzagentur.

When the TSOs compile the power balance, they focus only on national generation units and loads[2], thus neglecting the effects of the European internal market (cf. explanations in the main section above).

The stochastic parameters of various input data is simulated by applying historical peak load, historical time series of RES (empirical frequency distribution), averaged availability of thermal power plants and usage of experts‘ estimates (referring to the contribution of the peak load for pump-storage power plants).

The TSOs’ general procedure is based on a comparison of available capacity (reduced by a reserve for ancillary services) and on the highest load likely to be covered in Germany (cf. Figure 2.2). When assessing the power balance, the main figure is the remaining capacity at the point of time of the annual peak load.

The TSOs require that – compared to the annual peak load – the available capacity of RES (included biomass) is 99%. For the conventional power plants it is determined which power is available based on unscheduled unavailability for each primary energy source. The parameters determined for each technology are summed up[3].

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7 LOLE (abbreviation for loss-of-load-expectation) and ENS (abbreviation for energy not supplied)

This study focuses on the development and application of a new approach of monitoring system adequacy considering the changed requirements and realisation of the current power system (cf. the following section of the main part). The study deals with this issue from a separate perspective, not considering the TSOs' current proceedings described in this side-note. Nevertheless, based on the specific status quo of the TSOs' monitoring options of further development are feasible. First approaches are outlined in the enclosure A.

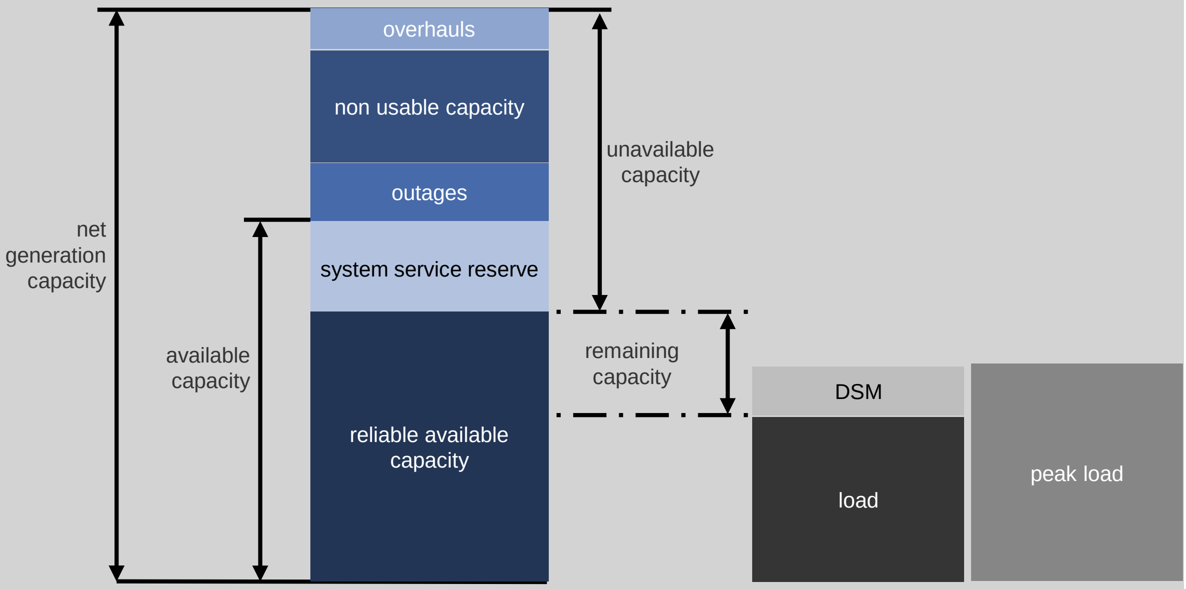

Figure 2.2 Methodology used by the German TSOs assuring capacity balance

[1]At the given point in time when submitting this study this description refers to the German TSOs' most recent report regarding power balance dated 30 September 2014.

[2]This is completed by load and generation units technically to be assigned to the German electricity supply system, like in the public electricity supply of Luxembourg.

[3]Totalizing 99% of available generation capacity resp. of outages rates of each technology / primary energy source implicitly assumes the correlation of availability of each technology.

2.3 Challenges and need of adjustment

As mentioned previously, the methodical approach for the monitoring of system adequacy should consider the characteristics of the European electricity supply system, and particularly the growth of the RES-production. The methods, currently applied, mostly fall short, in particular as they do not consider the indicators from a transnational perspective. Moreover, they are too much based on deterministic approaches.

The requirements for the technical models do not only refer to calculation methods but also to the available input data. At the same time, indicators respectively parameters of system adequacy particularly covering the probabilistic character of system adequacy in a sufficient manner should be applied for the generation of results.

Requirements on calculation methodology and input data

The transition towards a RES-dominated power system and the aspired completion of the European internal market require – when assessing system adequacy – the consideration of:

- **Stochastic character of input data:** It clearly refers to an intermittent RES-production, the load as well as the availability of conventional power plants. Stochastic characters mainly include the distribution of available power units as well as the time weather dependences regarding load and RES. In particular, the stochastic behaviour as well as the daily, weekly and annual time dependence of the load, or the annual and daily time dependence of the infeed provided by RES are emphasized. Stochastic dependences (in particular correlations) between the different input data have also to be considered. It is conceivable that certain weather and/or day-time conditioned effects influence the load level, and the availability of an intermittent generation. Indeed, in Central Europe the hours having an especially high demand normally occur during late afternoon / early evening on winter days. During this time of the day, however, photovoltaic units will not contribute to any load covering due to the solar altitude in Germany. By neglecting this correlation with regard to system adequacy, possibly occurring hours of scarcity would be underestimated, as this neglect implicitly assumes that high photovoltaic infeed occurs with the same probability at times of medium load – as during day-time on summer days – as during times of high load at winter evenings. On the other hand, hours with especially high demand in southern countries in summer occur during daytime when a considerable photovoltaic in-feed is to be expected. In this case, the use of an average probability per year would in particular overestimate the occurrence of critical hours.

- **Geographical effects**
    - **Functioning of the European electricity market:** The German electricity market is part of a European electricity market which aims at the transnational balance of supply and demand. A single national approach, the assessment of system adequacy solely based on national load and production, only has a very limited practical relevance due to neglecting functioning and effectiveness of the European electricity market. On the one hand, over-capacities in one country can help to cover the load in the neighbouring countries. On the other hand, considerable portfolio effects for the load, and the RES as well as for power plant outages exist on the European electricity market. Thus, the assessment has to consider the transnational effects in an adequate manner, even if the question of system adequacy is of interest only to one specific country.
    - **Portfolio effects with load and RES-production, and power plant outages:** On the European electricity market – in particular, by extending the considered geographic scope – stochastic effects are important, such as national peak loads or low RES-infeed which do not occur simultaneously. Likewise, power plant outages occurring in larger areas cause considerable portfolio effects. For that reason, control reserve is currently used allowing for a transnational approach.
    - **Cross-border transmission capacities**: The exchange of electricity between countries – which is required to be able to use the aforementioned portfolio effects - is limited by available transmission capacities. The amount of capacities and consequently the relevance of this limit differ from border to border. For the system adequacy of relevant peak load situations it can be assumed that in general, the power plant fleets operate close to their capacity limit. Under these assumptions it could consequently be concluded for certain country borders that due to high available transmission capacities they do not have any limiting effects. Thus, balancing potential resources resulting from demand and generation-side can be applied in total. On the other hand, the transmission capacity between certain countries / part regions could be so low that it has a limiting effect in nearly all cases and consequently does not admit any relevant exchange between these countries / part regions. For any other border it can hardly be estimated ex-ante whether – in the case of scarcity – transmission capacities have any limiting effect. These issues are quite significant for a proper assessment methodology.

- **Time-coupling and storage constraints:** If countries have a significant share of hydro generation in (pump) storage power plants (alpine and / or Nordic countries), time-coupling constraints have to be considered in order to record properly the generation availability of these (pump) storage power plants. The available generation capacity depends on the installed turbine sizes, the available storage volume, and on the natural inflow, and it depends on the pump capacity in case of pump storage power plants. If only one single hour was relevant to determine the achieved level of generation assessment, this technical boundary condition could be neglected. It can be assumed that transmission operators align the storage capacity by following the market-price signal so that the filling level of the storage reservoirs does not imply restrictions. In practice, however, more than one hour is relevant to completely determine the level of system adequacy. These time-coupling constraints could only be neglected if it could be assumed that potential hours of scarcity – with regard to the volume of the storage reservoir – diverge to such an extent that the storage reservoirs will be sufficiently refilled. This could be the case if the storage is refilled by pump storage or natural inflow before another hour of supply shortage occurs, or if the storage capacity is sufficient as is the mainly the case in storage power plants. However, it is not always possible to estimate this issue ex-ante as in such a case partly complex interrelations exist.
- **Further flexibility options:** While solely the availability of generation has been the decisive factor for balancing supply and demand (including the flexible cross-border exchange of generated electricity) demand side flexibilities, so called Demand Side Management (DSM), as well as the further including of emergency power systems[8] will become more and more important for system adequacy. DSM is the demand-sided reaction on market-price signals, in particular the decreased consumption in cases of scarcity. Such options of flexibility – as far as they are predicted – have to be considered in an adequate manner.

This study has picked up on these requirements and has developed a new methodology of assessment for system adequacy. This methodology is based on a stochastic, cross-border, and time-coupled simulation approach between the generation and the shortly price-inelastic share of the load. The calculations effected by this method are based on an extensive designs of RES infeed time-series based on historical weather years and time-series of demand for the same

[8] Emergency power systems have been used to an only limited extent on the electricity and reserve control market. In order to have a proper applied monitoring methodology, available capabilities are to be recorded in the future (by the TSOs and the Bundesnetzagentur).

weather years as input data. This was necessary in order to reflect their stochastic behaviour. Section 3 describes the methodology and the applied input data.

New parameters for monitoring and assessment of system adequacy

The calculation process and even more the applied parameters should include the probabilistic character of the system adequacy. In such a case various parameters are eligible, partly being internationally applied when system adequacy is discussed:

- **Load Balancing Probability (LBP):** The LBP describes the probability to completely cover the load (i.e. a balance between generation and the short-term price-inelastic share of the load[9]) without any further measures[10] and under consideration of the available generation and usable DSM potentials. It indicates with which probability the remaining capacity exceeds or is equal to zero, i.e. it shows the difference between available generation capacities and the short-term, price inelastic share of consumption load available at a given point in time.

  In the international context, the inverse value, i.e. loss of load expectation is often applied instead of the LBP[11]. Additionally, it is related to a time period per year and is also referred

[9] It indicates the share of load not responding with DSM to price signals of the electricity market.

[10] The dimension of further measures in order to achieve a balance between generation and load, also depends on the measures which have already implied when determining the LBP, resp. the probability of load surplus. The more measures have already been implied when determining the remaining capacity, the less it can be expected that any further measures are available in order to avoid a real load surplus with a negative remaining capacity. In general, a resilient determination of the LBP should aim to imply all measures in a manner as comprehensive as possible which support the balance between supply and demand. This mainly refers to the exchange on the European electricity trading market and the DSM.

[11] The probability of load surplus indicates the probability with a remaining capacity smaller than zero. When interpreting the probability of load surplus it has to be considered that load surpluses are controllable in many cases without the consumers being affected (cf. sector 2.1): clearly when market-based imports and more over further measures, such as emergency reserves of the national and international TSOs are considered on a national level.

to as LOLE[12]. The calculated value can be interpreted as the expected number of hours per year in which the value of the remaining capacity is smaller than 0. Based on the approach of LOLE several European countries have defined national thresholds for a minimum of system adequacy. Theses defaults differ between a LBP of 99.97% resp. 8757 h/a (a LOLE of 3 h/a) in France and Great Britain, and a LBP of 99.79% resp. 8742 h/a (i.e. a LOLE of 18 h/a) as default in Belgium. However, national approaches ignore the effects of the European electricity exchange[13]. Thus, these approaches of national target parameters for the system adequacy are only useful to a limited degree.

- **Probability of Energy Served (PES):** This parameter reflects the share of consumed electricity which can be covered without further measures[14] under consideration of the available generation and usable DSM potentials. The PES does not only imply the number of hours in which the short-term, price-inelastic load can completely be covered, but it considers the extent of load surpluses occurring. Thus, this parameter explicitly takes into account that in the case of a possible load surplus no geographical power outage ("blackout") occurs but at most a (small) share of consumption would be pertained by compulsory shutdowns effected by the TSOs ("brownout") (cf. also section 2.1). In general, the PES is the more conclusive parameter than the LBP.

In principle, the LBP as well as the probability of energy served (PES) – or in combination – are suitable as probabilistic parameters for the assessment of system adequacy. As in the international approach the LBP and probability of load surplus are currently more often applied as parameters of system adequacy, the quantitative results given in section 4 only pertain to the LBP.

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[12] LOLE: Clipped form for Loss of Load Expectation (s. a. explanation of probability of load surplus)

[13] Especially, a consideration only from a national perspective can lead to a false interpretation when these parameters are calculated and fixed, if such a national consideration does not take into account any further available measures (such as electricity exchange using portfolio effects). It means that it might very well be possible that a complete meet of the demand, within the calculated hours with a remaining capacity smaller than zero, occur.

[14] For the availability of any further measures refer to LBP.

3 Transnational monitoring of system adequacy - common methodology and specific approach

The analyses submitted in this study have aimed a transnational monitoring of system adequacy covering Germany and its geographical and "electric" neighbours for a time horizon up to the year 2025. Based on the requirements set out in section 2.3, it was - in a first step - necessary to develop a monitoring method fulfilling the given requirements. At the same time, a data-base meeting these requirements had to be developed in order to have a sufficient basis for the calculations. Figure 3.1 gives an overview of the methodology approach pursued in this study.

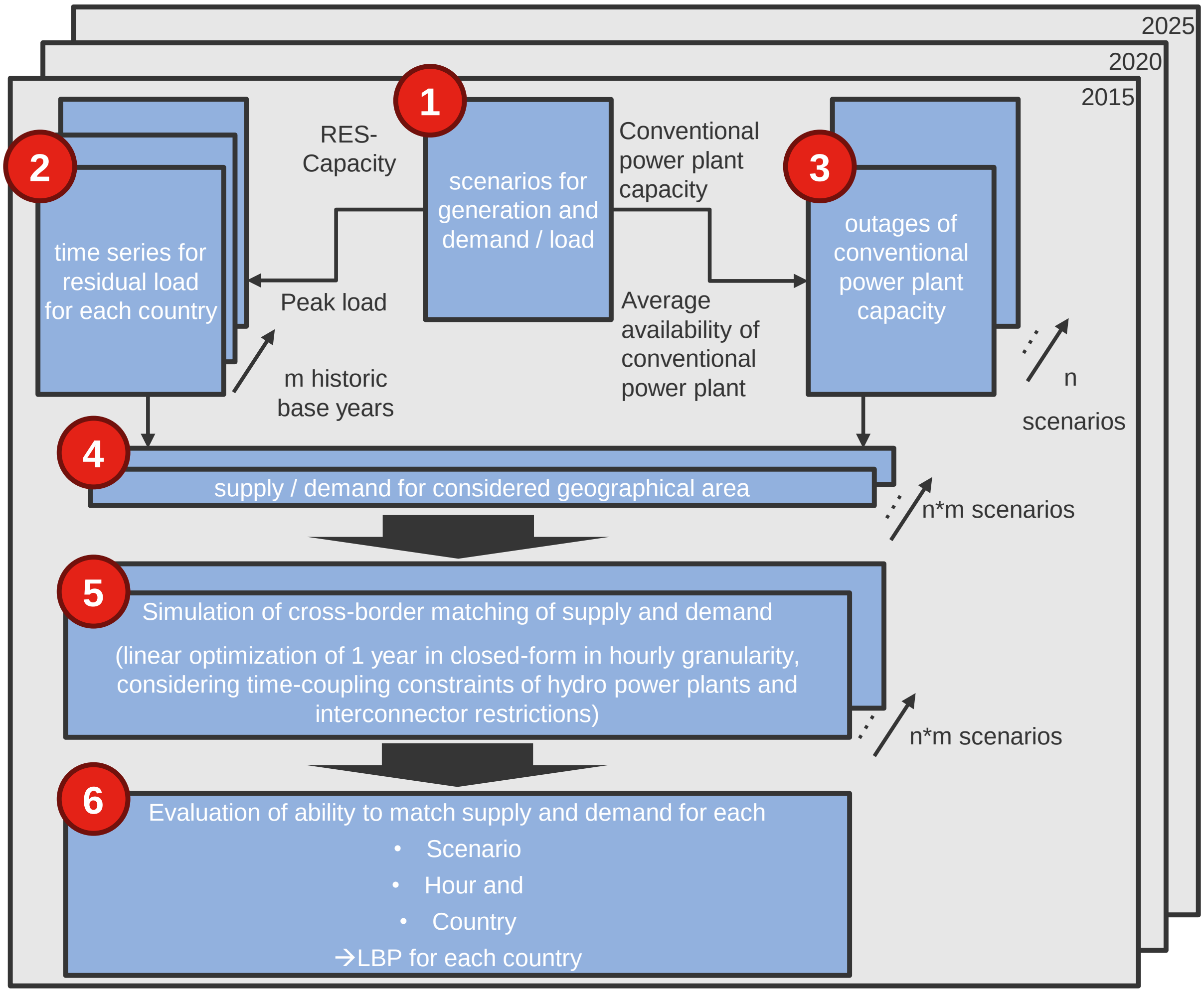

Figure 3.1 Overview of the methodology approach for the transnational assessment of system adequacy

Based on a scenario – for the investigations of this study exogenously accepted – regarding the development of the installed RES-generation capacities, the peak load, and of the conventional power park, and the determination of further central regulatory parameter (❶, cf. section 3.1), the time series are to be developed for the residual load per country and the considered base years (❷, cf. section 3.2). These time series are determined by simultaneous historical load and weather data for each considered region thus submitting the regional and timely correlation between load and intermittent RES production. In order to record the stochastic behaviour of each parameter in a sufficient manner, three time-series each including one year with an hourly time resolution for each considered forecast year (2015, 2020 and 2025) were developed based on various historical weather years. This investigation uses the weather years 2010, 2011, and 2012. Furthermore, 333 outage scenarios – based on the assumptions concerning the development of power parks – have been developed regarding the availability of conventional power parks (❸, cf. section 3.3). Each scenario – again for one year in an hourly time-pattern – investigates for each power plant and each considered hour — according a stochastic process that describes typical outage rates — whether the power plant is available or not due to a stochastic outage. Thus, the submitted investigations include 333 random-based outage scenarios for each considered forecast year.

The three time-series of the residual load per forecast year (❷) and the 333 outage scenarios (❸) are combined in total to 999 load/ generation scenarios (❹)[15]. These scenarios are used as input data for a simulation of transnational load covering (❺, cf. section 3.4). For all 999 scenarios for each forecast year (2015, 2020 and 2025) considering each region and each time-series per year this simulation investigates whether the load in each considered country — under consideration of at the available generation and the potential of DSM — can be covered at any time. At the same time, the essential technical regulatory conditions, esp. restrictions of hydro thermal power plants and available transmission capacities are taken into account.

By means of the results obtained in this simulation, the LBP can be calculated for each considered forecast year and region (❻, cf. section 3.5).

[15] Pre-investigations concerning the convergence behavior of the stochastic simulation have shown that the chosen number of 999 scenarios is (more than) sufficient for the considered systems.

3.1 General specifications and assumptions

The time horizon and geographical scope have to be determined in a first step. This study refers to a time horizon up to the year 2025 considering the base years 2015, 2020 and 2025. Thus, in particular the time period of the complete German nuclear phase-out is taken into account.

Figure 3.2 shows the countries selected as a geographical scope[16]. The considered region includes Germany and its geographical and "electric" neighbours (incl. Norway, Belgium, and Italy). Thus a region is investigated in which – especially due to significantly expanded transmission capacities, and for instance almost complete integration into the European market coupling – an important step towards the completion of the internal electric market has already been achieved, even though further steps towards this completion are still required.

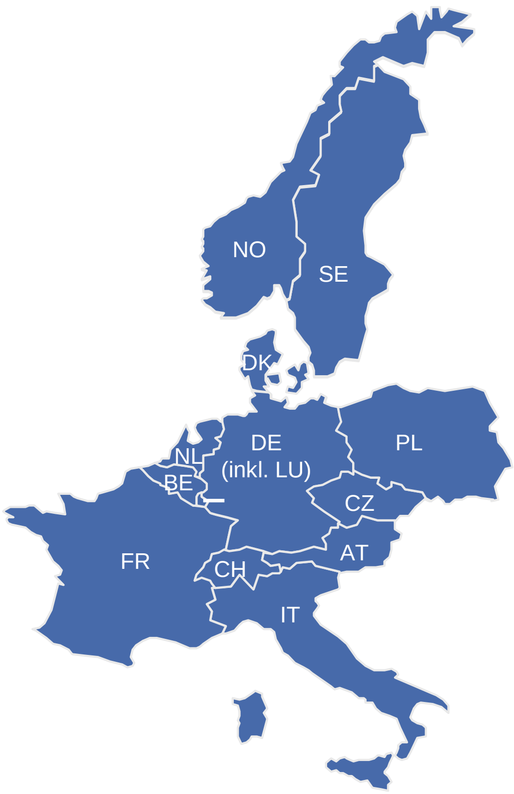

Figure 3.2 Geographical scope for the analyses of this study

In general, the selected time horizon up to the year 2025 implies that for such a scenario looking far into the future the developments of relevant input parameters, such as of conventional power

[16] A transnational cross-border exchange applied in countries outside this geographical scope has been neglected.

plants, of RES production, and of load and the potential of DSM can only be estimated with considerable uncertainties[17]. In addition, on the electricity market processes of adjustment for the power plant capacities and the use of DSM reacting on possible capacity scarcity or surplus capacities are to be expected, incited by the electricity price. In case of capacity scarcity, which are likely to occur, options of flexibility such as DSM potentials and already existing emergency power systems can be utilised, or new engine based power plants and unitized gas turbine power plants.

At short notice, the development of installed power plant capacities can comparatively be estimated fairly accurately. The expected launching of power plants (due to the lead times for their construction) within the next years are largely known. With regard to certain RES-technologies this issue, however, is only appropriate in a limited manner. At least for Germany, power plant shutdowns can be estimated under consideration of the publications of the Bundesnetzagentur. The short-term feasible reactions of adjustment, however, can be underestimated, as the development of DSM or the subsequent shut down of currently non-economic power plants are feasible in a considerably shorter time period reacting on the signals of the electricity price due to scarcity[18]. For a longer time horizon, especially 2025, but also the year 2020, the development of the conventional power plant fleet and the use of the DSM can only be forecasted under considerable uncertainty. Within this context policy makers' decisions, not yet adopted in any political-regulatory manner such as the market design, may perhaps be decisive.

By means of simulation approaches (i.e. on the basis of electricity-market models), it is generally possible to forecast the development of the power plant fleet (and the development and utilisation of the demand flexibility and of the emergency power systems) with regard to certain assumptions concerning the market design. This issue allows that forecasts as data basis for the long-term assessment of system adequacy can generally be improved. The experience, however, indicates that the results of such simulations strongly depend in some parts on assumptions (in particular regarding the development of economic regulatory conditions and the actor's behaviour) and on the precise parameterisation of calculation models. Furthermore, an adequate parameterisation requires a very detailed and thus, a complex mapping of national data (regarding the technical characteristics of power plants or the public subsidy mechanisms such as for

[17] Moreover, the load currently available cannot be completely measured.

[18] In addition, further shutdowns have to be expected in case of considerable overcapacities.

CHP plants). To this end, extensive and detailed models present the general uncertainties of all forecasts for this – relating to the possible development on the electricity market – extremely long period. Due to the close schedules, we have decided to apply only an exogenous, public available and hence transparent scenario for the investigations of this study.

The investigations are based on the "best-estimate" scenario, the so-called "scenario B" of the SOAF (System Outlook and Adequacy Forecast) 2014-2030 of ENTSO-E [2]. The scenario includes "best-estimate" scenarios provided by the national TSOs regarding the developing (peak) load, the conventional hydro thermic generation capacities, the RES generation capacities, and the utilised load management for the year 2015, 2020 and 2025, and for each considered country. With regard to the development of conventional capacities, it takes into account those types of new power plants (and shut-downs), which the TSOs classify as realistic ones, as well as those power plants the TSOs consider as probable to be realized. [19].

This "best-estimate" scenario of the European TSOs based on the investigations works on a potential development, but not the only possible one. In the future, various ways of development are possible resulting in various LBP parameters.

3.2 Modeling of time series and residual load

To analyze the development of the system adequacy and the European portfolio effects from load and renewable energy, it is in the first place necessary to assess the residual load.

In the context of this study, the residual load is defined as the difference between the hourly electricity demand (load) and the electricity generated from renewable energies. Therefore, it is the proportion of the load that needs to be covered by conventional power plants, storage and pump storage power plants or by using DSM.

The following will explain the basis on which the residual load is determined, in terms of data and methodology.

[19] ENTSO-E comments in [2]:"This bottom-up scenario gives an estimation of potential future developments, provided that market signals give adequate incentives for investments."

Load data

To calculate the hourly load of the countries considered, we used ENTSO-E's[20] published historic consumer load data ('hourly load values') in hourly resolution, for the years 2010, 2011 and 2012. Due to the measurement method used, this load data does not entirely include consumption.[21] The hourly load data are scaled for the base years (2015, 2020 and 2025) in such a manner that the resulting maximum load corresponds to ENTSO-E's SOAF 2014-2030 (Scenario B) projected maximum load for the specific base year.[22] This approach ensures that the cyclical load structure of the considered historic year, as well as the yearly maximum load of the respective forecast (including the missing consumption), is taken into consideration for each country.

Development of renewable energy power plants

The assumed increase in the installed RES-E (renewable energy sources for electricity) capacity for the years 2015, 2020 and 2025 is based on Scenario B of ENTSO-E´s System Outlook and Adequacy Forecast (SOAF) 2014-2025. Figure 3.3 shows the aggregated capacities of all the countries considered, differentiated by energy source for each base year.

Overall, we estimate there will be a 40 % increase in the installed capacity of RES-E between 2015 and 2025.

[20] cf. [2].

[21] The published consumer load profile for each country is not complete. For example, for Germany the industrial self-generation and traction power from own generation is not included.

[22] cf. [1]. The yearly peak load in this case derives from the entries in the rows 'load' and 'margin against seasonal peak load'.

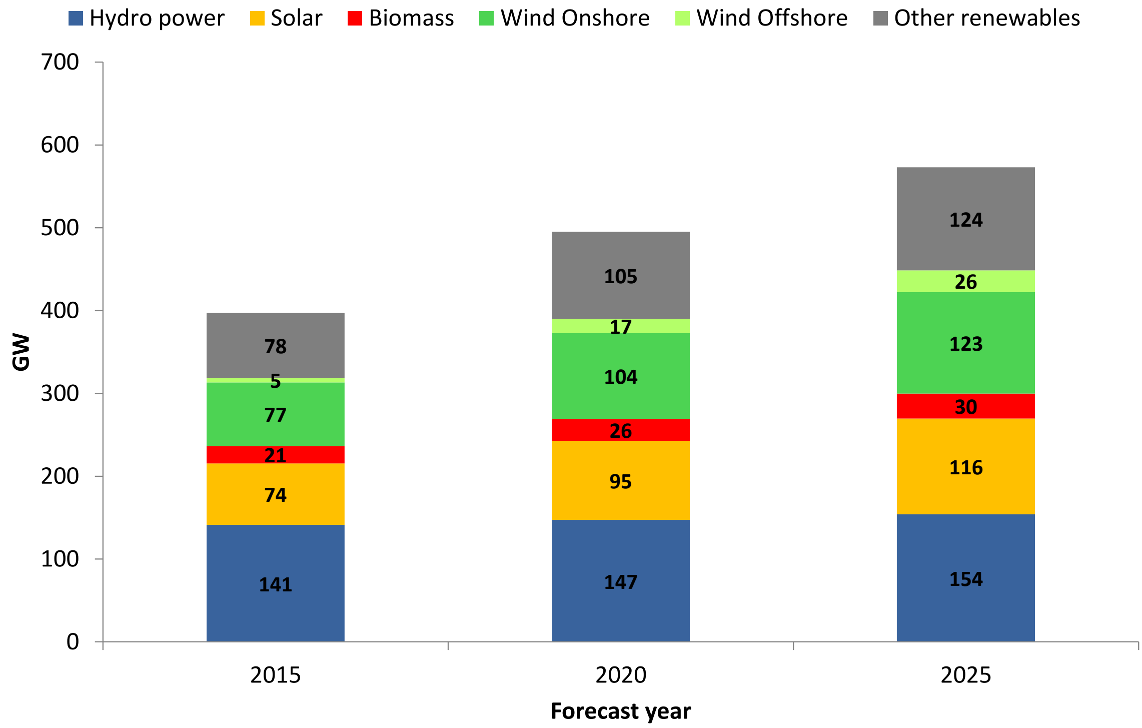

Figure 3.3 Assumed installed capacities of RES-E for the countries considered

Generation infeed from renewable energy sources

In respect of onshore wind energy, offshore wind energy and photovoltaic energy, company owned, high-resolution, hourly infeed curves are used. These are calculated on a European scale on the basis of r2b energy consulting's extensive geological, geocoded and meteorological databases that, among other things, include years of hourly weather data from the Deutscher Wetterdienst (DWD) starting in 2007 based on the COSMO-EU model.[23] According to the modeling of the load time series, for the calculation of renewable energy generation meteorological data for the years 2010-2012 is used. This way it is possible to map implicitly possible stochastic dependencies between the load and RES-E production.

In addition to the meteorological data, a European wind turbine system database was used in context of this study. This database contains information on nearly all existing systems, as well

23 The model area from the COSMO-EU spans over nearly all of Europe including the Baltic Sea, the Mediterranean Sea and the Black Sea with a grid pace of 0.0625° (~ 7 km) and 665x657 grid points. It contains hourly data on wind speeds, temperature and pressure at different heights as well as the roughness and global radiation.

as systems under construction and planned onshore and offshore wind parks.[24] After assigning a grid point of the COSMO-EU model[25] to each wind park, using a geological information system (GIS), it is possible to obtain local wind speeds at different heights for each allocated wind energy system. For each grid point, these hourly wind speed curves are converted to hourly generation infeed of the wind energy power plants allocated to the grid point. To achieve this, the onshore and offshore wind energy systems are specified by sub-class. These different technology sub-classes are determined on the basis of an evaluation of the installed capacities, as well as other relevant indicators such as hub heights. There is also an evaluation of future technology development, considering the development of weak-wind systems as well as strong-wind systems. The technologically specific and characteristic performance curves[26] assigned to each class determine the base of the calculation for the hourly infeed.

Photovoltaic electricity infeed in Germany is based on our company owned database, with a degree of accuracy representing every single existing photovoltaic energy system. In the European context the calculation is based on geocoded information regarding the installed capacity of all existing systems in each country and region. The model calculation of hourly infeed is based on the consideration of different technologies and corresponding efficiency factors, as well as the hourly global radiation, the surrounding temperature and the performance ratio[27].

In respect of electricity generation from biomass, only the inflexible part is taken into account when determining the residual load.[28] For this part, a constant hourly infeed is assumed. The infeed from biomass results in the multiplication of the SOAF Scenario B's capacities with the

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[24] It contains data about geo-location, installed capacity, hub height, turbine type, developer and date of installation.

[25] [4]

[26] A performance curve is a discrete representation showing the produced energy corresponded to the actual wind speed.

[27] The performance ratio describes the relationship between the actual and theoretical energy output of the PV plant. It is a measure of the quality of a PV plant and is therefore often described as a quality factor.

[28] In the context of this analysis it is assumed that the inflexible part of the electricity generated from biomass decreases; starting from 85 per cent in 2015, down to 70 per cent in 2020, and finally down to 50 per cent in 2025.

inflexible part, and the country specific full load hours of biomass. For the determination of the full load hours, the ENTSO-E Yearly Statistics & Adequacy Retrospect (YSAR) 2012 is used.[29] In this study, flexible biomass plants are treated as conventional thermal power plants.

In respect of electricity produced from run-of-river, the monthly generation data is based on the ENTSO-E statistics portal[30] and transformed to a constant hourly generation per month[31]. The infeed increases proportionally to the installed capacity, in compliance with the SOAF data.

The renewable energy sources resulting after the subtraction of biomass, photovoltaic, on- and offshore wind energy and run-of-river of the scenario B of ENTSO-E's SOAF 2014-2025 are taken into account using constant hourly generation.[32]

3.3 Modelling conventional power plants, flexible RES production, and transmission capacities

As already considered in section 3.1, the development of conventional power plants is based on the forecasts taken from the ENTSO-E SO&AF 2014 (scen. B). This scenario includes "best-estimate" scenarios on the development of the total net installed capacity for each country and each primary energy source. Figure 3.4 shows the development of the net installed capacity for each country. In addition to the development of the conventional generation capacity, figure 3.4 describes how the annual peak load and the DSM potential evolve in accordance with the scenario.[33]

The development of the conventional power plant fleet, i.e. the investments in generation units resp. the shut-downs, is based on the aforementioned scenario B in an exogenous manner. The

[29] YS&AR 2012 table no.1 - operational data 2012. For Belgium, Czech Republic and Poland the National Renewable Energy Action Plans (NREAP) 2005 are used, and for Italy the data of the "GSE" agency are used [5].

[30] ENTSO-E Data Portal / Country Packages ([9]).

[31] If the case of missing data occurs, national statistics are used as a fall back.

[32] It is assumed that for Italy the other renewable energy sources consist mainly of geothermal power plants. For these plants 6,000 full load hours are assumed. For the other renewable energy sources in other countries an average of 3,000 full load hours are assumed.

[33] For each year the scenario is based on one value related to summer and winter. As far as these parameters differ, figure 3.4 shows the higher value.

scenario only assumes the development of the total installed net capacity. For such a reason, it is explicitly not possible to make any distinction between new investments, shut-downs, and thus assumptions concerning the development of the power plant age structure.

When modelling the power capacity available to cover the load, a process which is relevant to assess the system adequacy, the non-available generation capacities are to be subtracted from the net installed capacity due to planned maintenance and overhauls processes. For this investigation, we have determined the parameters of an average foreseeable share of unavailable generation of power plants – again derived from the ENTSO-E data, scenario B of the SOAF 2014-2030 – and accordingly reduced the total net installed capacity for each primary energy source in a first step.

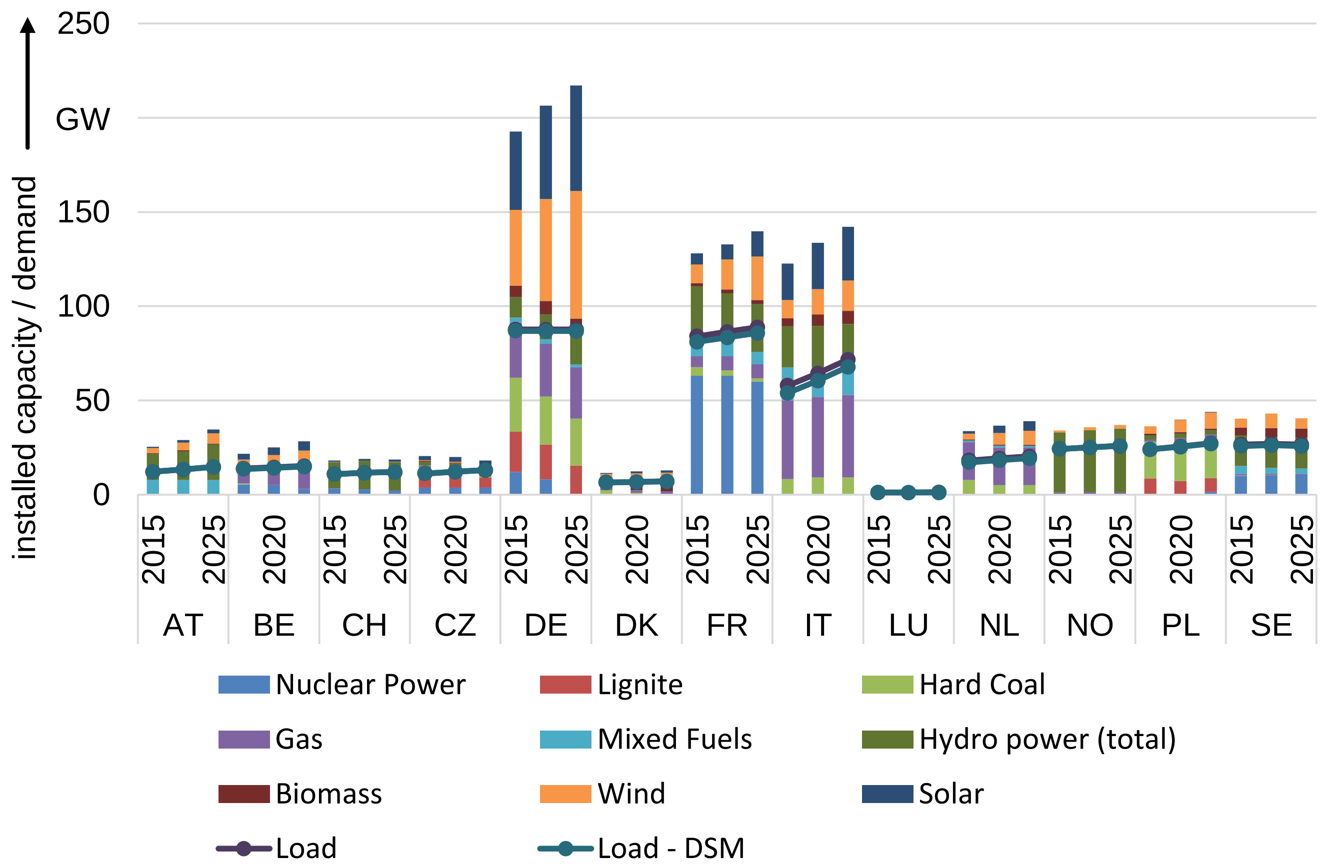

Figure 3.4 Development of conventional generation capacity, installed RES-production and annual peak load with / without reduction of DSM-potentials according to the ENTSO-E data, scenario B of the SOAF 2014-2030

In addition, power plants are not available due to any unforeseen stochastic outage. As already described, 333 stochastic scenarios for the available power capacity have been performed for the three time-series of residual load for each considered base year. As applied in [7] we have determined specific technical average parameters of unforeseen, non-available power plant units based on empirical parameters provided by r2b energy consulting. The scenario B of the SOAF 2014-2030 of the ENTSO-E only includes the data of the total installed net capacity for each primary energy source; it does, however, not refer to any single unit. For this reason, it was necessary to base the calculations on typical unit sizes per technology. These data are available at Consentec and derived from a database of the European power plants. Based on this scenario, it is calculated for each power plant unit by means of an evenly spread stochastic drawing whether or not the power plant is available during a certain hour[35].

We have assumed that thermal power plants with combined heat and power, "CHP plants", are dispatched to the electric power demand during situations with high residual load. Thus, during such hours of supply shortages these plants are not limited in generation capacity related to heat load covering but are available with the entire installed capacity.

For reasons related to calculations – in order to control the computational time for the stochastic simulation (cf. section 3.4) – technical characteristics of the thermal power plants going beyond the availability of power plants and the installed capacity have been neglected for the present investigations.

In addition to the thermal power plants, hydro (pump) storage systems are relevant for covering the load and thus are to be considered appropriately. The installed turbine sizes are to be derived from the scenario B of the SOAF 2014-2030 of the ENTSO-E. Furthermore, (pump) storage systems are limited by the restricted reservoirs, the pump capacity and – if applicable – the timely distribution of the natural inflows, and with regard to the possible contribution of this power plant to covering the load. Accordingly, these resulting intertemporal constraints are to be considered when simulating the covering load (cf. section 3.4). Hence, the assumptions have to be made concerning the reservoir size, volume of natural inflows, as well as their timely distribution. The volume of the natural inflows (total volume per year and country) have been calculated depending on weather influence for the same weather years as they are based on

[35] In this case, only outages of the total power plant system have been considered and part-outages have been neglected.

calculated residual time-series according to published available data [8,9,10] . In order to control the parameter considered in the stochastic simulation (cf. section 3.4), pump storage and storage power plants are aggregated for each country to one pump storage plant and one storage plant.

For thermal power plants the electric efficiency factor of plants is only relevant to the volume of generation costs but not to the decisive question whether the system is generally available for covering load. This, however, is not readily applicable to pump storage power plants. The efficiency factor of a pump storage power plant is – in addition to the assumptions concerning installed capacity and reservoir volume – decisive for the question how much pump energy is to be applied in order to assure sufficient turbine capacity for covering load at a given point in time resp. time period. Pump capacity has to be provided by other generation units in advance. Under certain circumstances such a load increasing pump operation can cause recurrent supply shortages. This can – inter alia – depend on the assumed efficiency factor. For this reason, adequate assumptions have to be made. The present investigations have assumed an average efficiency factor of 80% for pump and turbine operation.

In general, biomass plants are separated into an inflexible and a flexible share, such as plants reacting especially on market-price signals. It can be assumed that only the flexible share of biomass plants are available assuring the entire installed capacity for covering load during supply shortages. However, used inflexible biomass and thus capacity being available are determined by other application strategies. Inflexible biomass plants are already considered in the time series of residual load as an invariable infeed (see section 3.2). For the future, it is to be expected that the share of flexible biomass plants is supposed to increase. The current investigations have assumed that the share of flexible generation to the entire installed capacity in biomass plants is supposed to increase from 15% in 2015 to 30% in 2020 and finally to 50% in 2025 in all considered countries. For these investigations flexible biomass plants are treated as conventional thermal power plants and their availability is accordingly modelled.

The share of available DSM potential for each country and year can also be forecasted according to scenario B of ENTSO-E’s SOAF 2014-2030. However, the potentials - forecast as available – seem to be rather small [7,11]. The present investigations assume that this potential in the case of supply shortages is entirely available and thus reduces with 100% availability the residual load which has to be covered by other available generation plants.

The assumptions regarding the development of the cross-border transfer capacities between the considered countries are mainly based on the evaluations of the ENTSO-E's *Ten-Year Network Development Plan* (TYNDP) [12]. If necessary, the assumptions have been completed by the information provided by national TSOs and published data of energy exchanges which need appropriate data like operators of market coupling.

3.4 Stochastic simulation approach

The methodology of calculating the load balancing probability depends on the considered system. In a system neglecting stochastic dependencies between input data such as transmission restrictions and time coupling, the probability distribution of the residual load can be determined by means of the mathematical method of recursive convolution. Thus, the parameters such as load and generation balance probability can be calculated from this probability distribution.

As described in detail (in section 2) stochastic dependencies between input data (e.g. between load and PV) as well as transmission restrictions of the cross-border capacities are relevant for the assessment of system adequacy in the current European electricity market. In case of hydraulic (pump) storage power plants intertemporal constraints cannot be neglected. This issue requires computer-based simulation approaches in a more complex manner.

This simulation verifies whether in each country the price-inelastic share of the load can be covered by available generation capacities referred to the available transmission capacities within the considered geographical scope. This issue requires to consider a longer time period – say, one year, such as in the present investigations – so that in particular the intertemporal constraints of hydro power plants can be reflected in an adequate manner.

In principle, the simulation validates whether a system made of equations and inequalities can be solved. It is subject to covering load in each considered hour and country. Further optimizations describe intertemporal constraints of reservoir including the natural inflows. Inequalities restrict the maximum generation capacities of the power plants and the maximum transmission capacities. Utilization of the conventional power plants, as well as of the volume of the reservoir and the cross-border capacities are the variables of the (linear) equation system.

If such a simulation based on equations and inequalities shows a solution, load can consequently be covered by means of the given input data during the considered year for the entire geographic scope (esp. assumptions concerning the time series for the residual load, natural inflow and available power plant capacity / outages). Under the certain considered scenario load balancing probability would correspond to 100%.[36].

If the system of equitation cannot be solved, load will not be balanced by means of the given input data in at least one country resp. one (part) region and one hour.

However, a single result is not sufficient to determine the load balancing probability as it is necessary to know how often and in which countries and regions load surpluses could occur. Thus, integrating slack variables will relax the equations of covering load. The simulation approach is based on a linear optimization problem which is subjected to the mentioned equations and inequalities of the linear system. The objective function is minimizing the number of hours having a load surplus in the considered scenario, namely a time overlapping for the entire considered year and region.

It has to be considered that this approach is based on perfect foresight (clearly relevant with respect to hydro storages) and only simplifies technical characteristics of thermal power plants for computational reasons.

The results of such an optimization enable to assess how often and in which countries and regions of the considered scenario load could be covered with simultaneously taking into account the considered preconditions. Such an assessment of system generation adequacy simulates a large number of scenarios – in the described case of investigations a number of 999 scenarios for each base year (resulting in the residual load of three weather years and 333 outages of the conventional power plants). This also relates to the term of *stochastic* simulation.

3.5 Calculation methodology of load balancing probability

As described in the previous section, an appropriate evaluation of the simulation results shows whether it has been possible to balance supply and demand for each hour, each country and

[36] This does not imply that for the considered year load balancing probability is equal to (nearly) 100% as for a number of scenarios have to be considered; it is the result of considering a number of time series of residual load and a large number of outages of conventional power plant capacity (333 outages each for 3 weather years).

scenario considering available generation, grid capacity and constraints of hydro storages. Vice versa, all hours having no entire load covering for all considered scenarios can be calculated in the same manner[37].

Load balancing probability ($LBP_{i,j}$) for each considered country *i* and for a certain year *j* is – over all *n**m* considered scenarios[38] - the quotient provided by the result of the number of hours with the covered load in country *i* in *n**m* scenarios and the number of all considered countries in *n**m* simulations.

3.6 Grading of methodology and model results

As already discussed in section 3.1 when explaining the general requirements and assumptions, the timely scope of consideration up to the year 2025 means a particular challenge for the assessment of system adequacy. The development of numerous parameters which affect the volume of system adequacy and thus the calculated load balancing probability can only be forecasted accompanied by considerable uncertainties for a forecast horizon in the far future[39].

This does not only apply with regard to a generally increasing uncertainty in the case of long-term forecast horizons, but in particular, as on the electricity market the installed power plant capacity and the utilized DSM potential develop dynamically. Both depend on the probability of possible capacity scarcity or overcapacities and on the electricity price signals being involved. With the emerging capacity scarcity, flexibility can be made favourable for the electricity market within a short time, such as DSM potentials and already existing emergency power systems. Furthermore, new engine based power plants and unitized gas-turbine power-plant could be installed.

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[37] In the case of a transnational approach – as being performed here – it has to be considered that the load surplus cannot clearly be referred only to one country of this region if a load surplus occurs in a shortage-free region at that time. This shortage rather refers to the total region. The calculation of the transnational country-specific load balancing probability and the probability of load surplus has to assume that the load surplus affects each country of the region.

[38] *n* relates to the number of considered outages (in this case 333) and *m* relates to the number of historical base years to determine several annual time series of residual load (in this case 3).

[39] Moreover, the current load cannot be completely measured.

The methodology of monitoring based on static forecasts (in other words, the direct requirement of a static forecast capacity-development without considering the dynamic adjustment process on the electricity market) cannot record such a dynamic process. This issue has to keep in mind when interpreting the results shown in the following section. In particular, this means that based on a monitoring, which suitable in terms of inputs and outputs as well as calculation methods, verifiable statements regarding system adequacy can only be derived for a short time-horizon, with other words, approximately for a time horizon for the next three up to four years. For this time horizon possible changes of capacities on the electricity market can be estimated in a relatively accurate manner. However, it is possible that achievable short-term adjustment reactions can be underestimated, as the development of the DSM or a consequent shut-down of currently uneconomic power plants are realistic within a significantly shorter time horizon, hence reacting on electricity price signals due to scarcity[40]. For a time horizon in the future such statements can only be of an indicative character, as the described dynamic effects cannot be reproduced in a sufficient manner.

Unlike the utilization of exogenous input data (i.e. the direct specification of a static forecast capacity development), the model-based investigation of the capacity development (i.e. based on an electricity-market model) can generally consider also dynamic adjustments on the electricity market –market-driven shut-downs or new installations of generation units as well as the development of DSM. The forecasts, which are used as data basis for the long-term assessment of system adequacy, can be improved by this process. However, uncertainties regarding the development of economic regulatory conditions and the actual realization of efficient adjustment processes (individual decisions of each market player) also remain if the input data are calculated in such a model-based manner[41]. In particular, this refers to long-term horizons, in which uncertainties concerning the economic regulatory assumptions and the realization of ad-

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40 In the case of considerable overcapacities further shut-downs are also to be expected.

41 In addition, the approaches for modelling the electricity market and the assessment of system generation adequacy should be consistent.

justment processes in market simulations can only be recorded by scenarios. Hence, even appropriate approaches for monitoring and simulation the electricity markets do not allow any absolute statement how the electricity market works with regard to the system adequacy[42].

[42] They have to be completed by the analyses concerning the potential flexibility options and possible obstacles for the adjustment processes on the electricity market.

4 Quantitative results

The following section describes the results of the quantitative analyses performed for this study. Section 4.1 summarises the analyses concerning portfolio effects related to the peak and the residual peak load in the considered region. These analyses show that considerable transnational portfolio effects for load and RES-production exist, and that they are supposed to increase due to the increased RES-expansion up to the year 2025. In practice, these portfolio effects can only be applied up to the volume of available cross-border transmission. In a first step, the considerations of section 4.1 neglect these restrictions. Section 4.2 summarizes the investigations for a transnational assessment of system adequacy. In addition to the portfolio effects of load and RES, the applied methodology takes into account inter alia the restrictions of the cross-border electricity exchange and the portfolio effects in case of power plant outages.

4.1 Quantitative analysis of European portfolio effects

The increase in the proportion of electricity generated from renewable energy sources will most likely be achieved through technologies whose generation is predominantly dependent on meteorological and climatic factors such as wind speeds, solar radiation and cloudage.

In contrast to energy generated using conventional power plants, storage power plants and pump storage power plants, electricity generated from renewable energy sources does not occur due to demand or on the basis of market signals. It results in changes of the residual load structure and challenges facing the power supply system. The influence of the RES-E infeed on the annual peak load is particularly interesting regarding system adequacy. In context of this study, the annual peak load is defined as the annual peak consumption which is regarded as a guide to determine how much power plant capacity must be available to ensure sufficient supply, without electricity imports or the potential use of DSM.

The extent of the impact of the RES-E infeed on the residual annual peak load differs from a European perspective to a purely national perspective. With wind power generation in particular, geological portfolio effects are also expected. Considering a regional wind front, for example, it is possible that the lack of wind energy infeed in one region is compensated by the high wind energy infeed in another region. In addition, European portfolio effects of consumer load need to be considered, since load peaks are usually not synchronized on a transnational level. Concerning our research on transnational portfolio effects, it is assumed that there are sufficient interconnector power lines between the countries. This is, based on the actual situation and the future plans of interconnector capacities, a valid approximation.

We examined which portfolio effects occur within the load and within the residual load. To do this, the structure and the maximum values for the load and the residual load for different historic weather years were analyzed. The process examines how different weather conditions and cyclical circumstances affect this. The outcome of our analysis for the weather years 2010, 2011 and 2012 are presented in the following.

To illustrate the transnational portfolio effects on the course of the residual load initially, the so-called (residual) load duration curves, which are determined by sorting the (residual) load levels in descending order, are only considered for one weather year. On the one hand, load duration curves and residual load duration curves – differentiated by energy source – are determined for each country. On the other hand, the (residual) load time series from individual countries is summed, and then a transnational (residual) load duration curve is derived. A comparison of the sum of the individual (residual) load duration curves with the joint (residual) load duration curve of the countries considered as a whole, reveals the extent of transnational portfolio effects.

Figure 4.1 shows transnational portfolio effects based on the total residual load for the years 2015 and 2025, using the example of the historical weather year 2012.

The dark gray curves represent the totalized load duration curves of the countries, while the light gray curves depict the load duration curves of the combined chronological load time series of the countries considered. The dark and light green curves represent the analogous relation for the residual load. Both times, in the case of the load duration curves and the residual load duration curves, the curves of the common time lines are shallower than those of the combined lines; whereas the difference in the course of the residual load duration curve is much more distinct. The common annual peak load is around 9 GW lower in 2015 and 10 GW lower in 2025 than the sum of the individual annual peak loads. In the case of residual annual peak loads (red circles), portfolio effects add up to 11 GW in 2015 and 20 GW in 2025.

It is thus seen that the different load structures in the various countries already lead to portfolio effects. The transnational portfolio effects are, in relation to the RES-E infeed, significantly more intense. This is largely due to the regional conditions within the countries considered, including very different wind speeds and global radiations. So, for example, a wind front does not occur in all countries simultaneously but has a time delay, or occurs to a lesser extent in other regions.

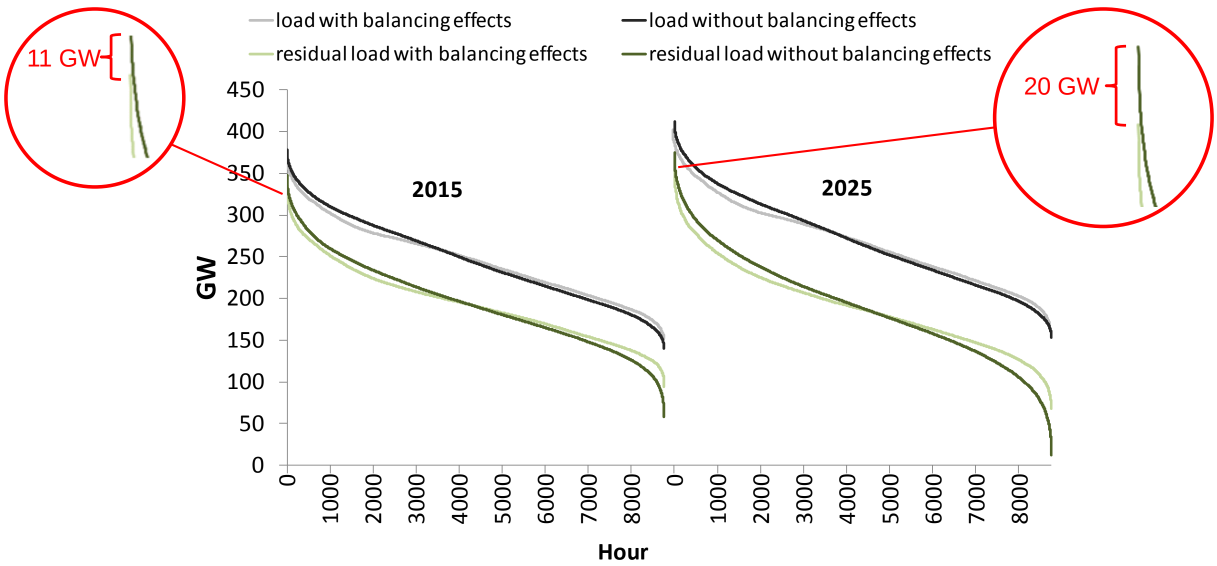

Figure 4.1 (residual) load duration curves 2015 and 2025 for the weather year 2012 (Source: own calculation by r2b)

The figure above shows the effects of increasing RES-E infeed on the residual annual peak load and transnational portfolio effects for an exemplary historical (weather) year 2012. In individual years, both the economic conditions (reflected in the load structure) as well as the weather conditions (reflected in the RES-E infeed) differ significantly. This may affect the residual load level, on the one hand, and, on the other hand, the level of transnational portfolio effects.

In figure 4.2, the variation of the residual annual peak load, as a function of the historical rule (weather) years 2010, 2011 and 2012, is shown for the forecast years 2015, 2020 and 2025. The necessary residual annual peak load to cover varies from 328 GW to 336 GW in 2015, and from 349 GW to 355 GW in 2025.

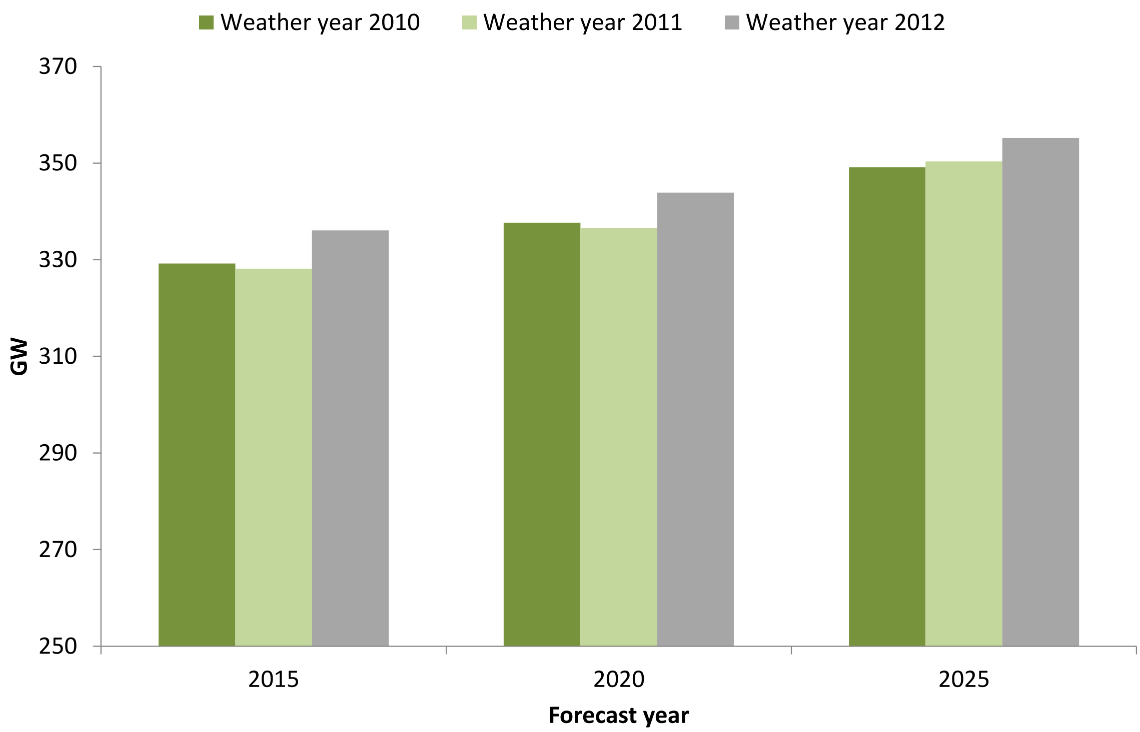

Figure 4.2 Development of the (residual) annual peak load (Source: own calculation by r2b)

The extent of the transnational portfolio effects, with respect to the residual annual peak load, differs from weather year to weather year more strongly than the level of the absolute residual annual peak loads itself. The left part of figure 4.3 shows the different extents of these portfolio effects in respect of the three considered weather years, for the base years 2015 to 2025[43].

However, the differences between the weather years diminish as more hours with the highest residual loads are considered. In the right graph in figure 4.3, those hours of the year are taken into account in which the residual load is higher than that (0.05) quantile of the residual hourly loads of the year. This corresponds to the 20 hours of the year with the highest residual loads. In this case the average portfolio effects in those hours are a maximum of 1.38 fold higher, on the basis of one weather year than those based on a different weather year.

[43] In determining the residual load on the basis of the historical weather year 2011, the residual annual peak load decreases due to transnational equalization effects particularly strongly; in fact almost twice as strong in 2015 and 1.35 times as much in 2025, compared to the weather year 2012.

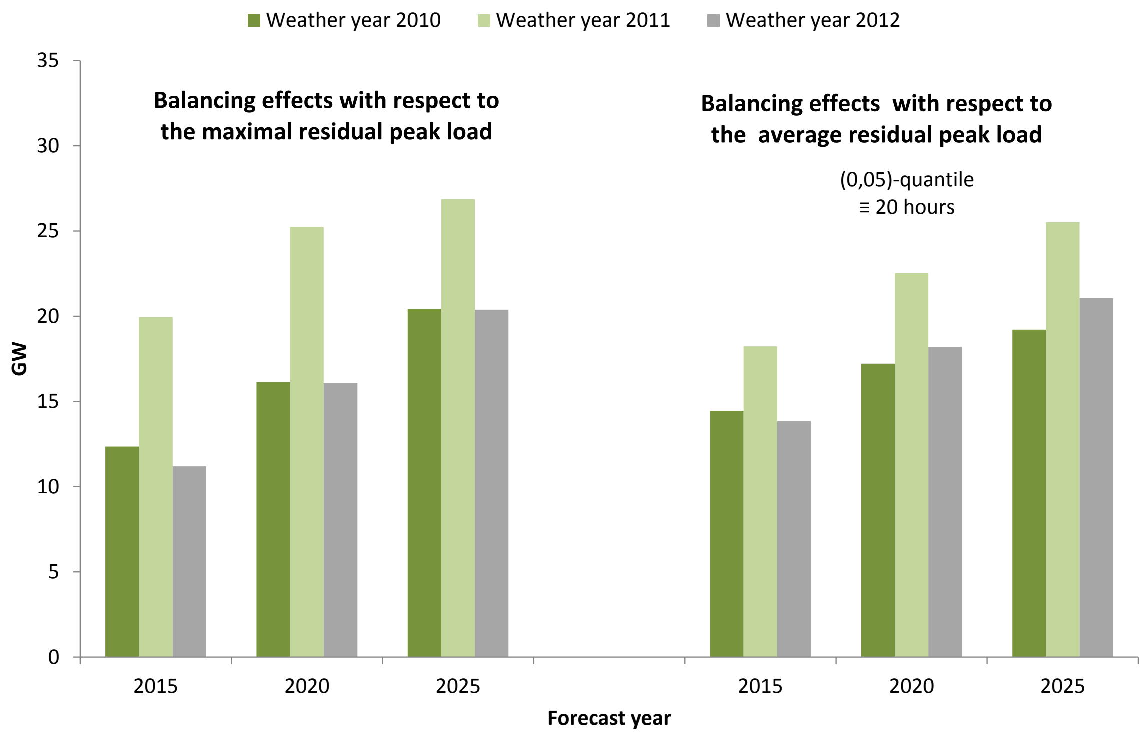

Figure 4.3 Development of the portfolio effects with respect to the (residual) annual peak load (Source: own calculation by r2b)

Table 4.1 gives an overview of all identified transnational portfolio effects, with respect to the annual peak load and the residual annual peak load for all considered weather and forecast years. The extent of the transnational portfolio effects, with respect to the annual peak load, strongly depends on the assumed economic conditions in the base year. The portfolio effects increase, due to the assumed country-specific increase in annual peak loads from 2015 to 2025, only moderately – up to 10%.

The portfolio effects with respect to the residual annual peak loads include both effects, those of the load as well as those of the RES-E infeed and thus those of the weather year. It should, however, be noted that the timing of the annual peak load and the residual annual peak load can, and most likely will, be different. Nevertheless, even in the hour of residual annual peak load, there will be transnational portfolio effects with respect to the load. The transnational portfolio effects with respect to the residual annual peak load reach values up to about 20 GW in 2015, and 27 GW in 2025.

Balancing Effects			
for residual peak load [GW]	**2015**	**2020**	**2025**
2010	12	16	20
2011	20	25	27
2012	11	16	20
for peak load [GW]	**2015**	**2020**	**2025**
2010	13	13	14
2011	18	19	19
2012	9	9	10

Table 4.1   European portfolio effects (Source: own calculation by r2b)

The results of the study show that the compensation effects are at least 10 GW for all three considered weather years at peak load in 2025. At the same time, the portfolio effects are, at the maximum residual load, at least 20 GW.

As a result, from a European view, the challenges for the power supply system and the system adequacy caused by the transformation to a system with an ever increasing share of fluctuating infeed from renewable sources are decreasing. The larger the geographical area in which the analysis of the residual load is performed, the more portfolio effects are observed in all areas. Thus, portfolio effects result from time delayed load curves and different weather conditions in different countries. In comparison to a smaller area, this results in a flatter residual load duration curve.

The absolute reduction of the residual annual peak load and the exact extent of transnational portfolio effects depend, however, on the observed weather year and the prevailing economic conditions of the specific year. However, in a transnational context the common residual annual peak load is at least 11 GW to 20 GW in 2015, and 20 GW to 27 GW in 2025, lower than the sum of the national residual annual peak loads. In practice, these portfolio effects – especially with regards to system adequacy issues – can only be harnessed within the scope of interconnector capacities between countries.

4.2 Determination of the load balancing probability

Based on the methodology approach and the assumptions described in section 3, calculations for the LBP are made by means of the simulation method developed for these investigations.

The load balancing probability as parameters for the monitoring and the assessment of system adequacy is calculated for the base years 2015, 2020 and 2025 for the region comprising Germany and its geographical and "electric" neighbour countries, in total 13 countries (cf.figure 3.2). Figure 4.4, figure 4.5, and figure 4.6 show the results.

Just from this selected transnational perspective, the system adequacy on the European electricity market – as discussed in detail above – can be measured and assessed under consideration of the more or less available and used options of the cross-border exchange.

For the base years 2015 and 2020, it has become a computational LBP of 100% for each considered country for the scenario B of the SOAF 2014-2030 of the ENTOS-E. This means that a balance of load and generation can be achieved in each single simulation per base year for 999 load/generation scenarios. It has to be taken into account that in purely mathematical terms the LBP is of 100%, in practice the probability is nearly 100%.[44]

In 2025, only in two countries (Belgium and France) situations occur, in which load balance is partly not possible. For 2025, in Belgium LBP of 99.99999% is calculated. In France a LBP of 99.99994% is calculated for 2025. This result corresponds to 5 hours of non-achieved load balance arising from about 8.75 millions of hours considered in 2025. When analysing the results, it should be considered that those tiny differences are no proof that there is a factual difference with regard to the achieved level of system adequacy.

[44] In fact, only a LBP of *nearly* 100% can be referred to as a technical system can only be available to an extent of nearly 100% but never completely of 100%. There is always a residual probability of extreme situations. Such a specific high but (very) unlikely non-availability of conventional power plant capacity resulting in a situation in which load and generation is not balanced did not occur in one of 999 scenarios investigated in this specific case. The same applies to a very unfavorable constellation of load and intermittent RES production that cannot be completely excluded. However the number of considered scenarios are in general sufficient to demonstrate the relevant stochastic effects. The pre-investigations we made concerning the convergence behaviour of stochastic simulation have shown that the given number of 999 scenarios are (more than) sufficient for these systems considered.

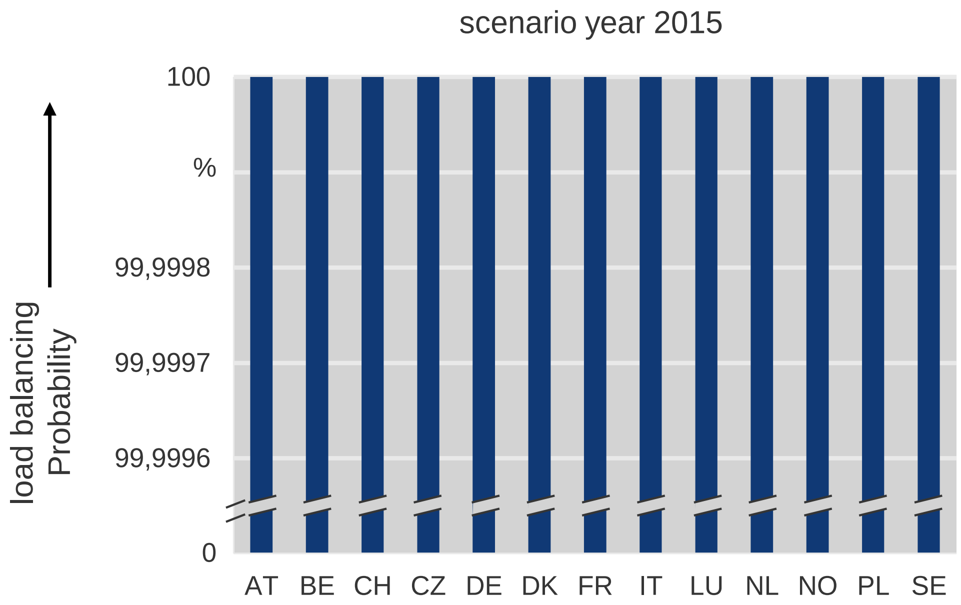

Figure 4.4 Load balancing probability for 2015 per country in transnational approaches (source: own calculation by Consentec)

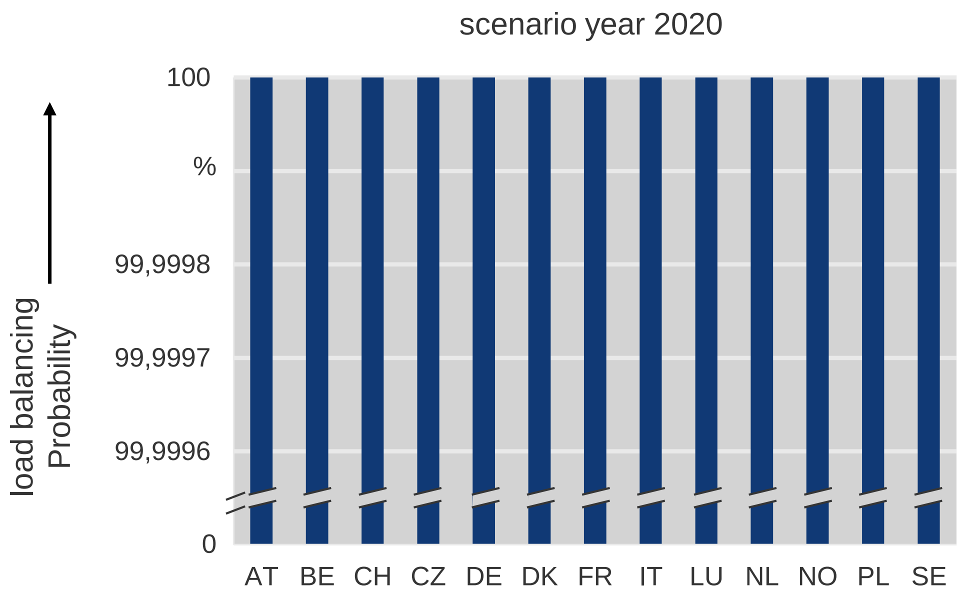

Figure 4.5 Load balancing probability for 2020 per country in transnational approaches (source: own calculation by Consentec)

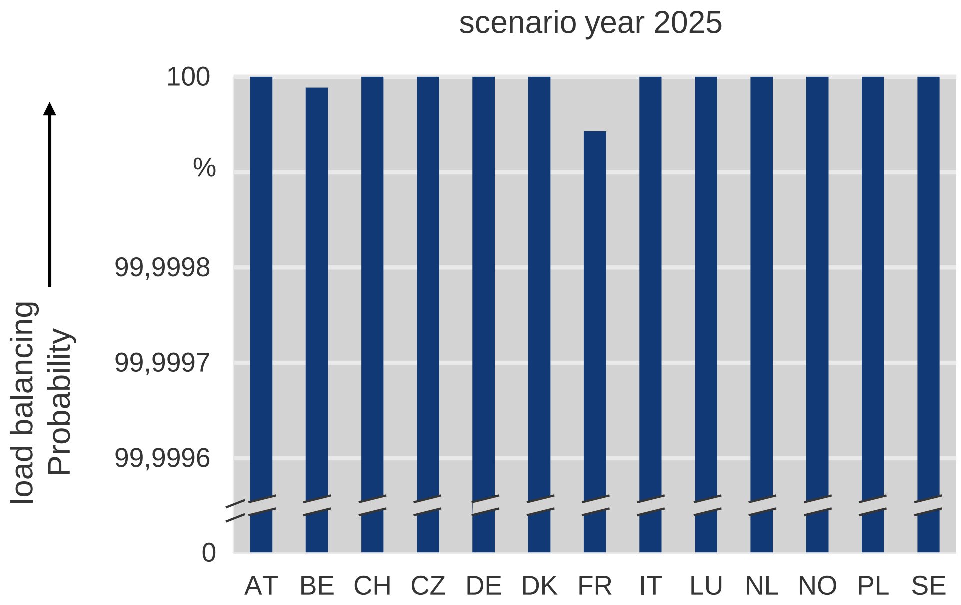

Figure 4.6 Load balancing probability for 2025 per country in transnational approaches (source: own calculation by Consentec))

In Germany and its geographical and "electric" neighbours, load and generation can very likely be balanced at any time – under consideration of transnational possibilities of exchange and in particular of the portfolio effects within this region – in the view of the "best-estimate" scenarios of the ENTSO-E for load and generation development up to 2025. However, these results especially depend on the assumptions made for the development of the demand and of the power plant capacities. The European TSOs' "best-estimate" scenario on which the investigations are based is a possible, but not the only conceivable development. Regardless of the actual future development of capacity, the investigations confirm the benefit of the transnational exchange of electricity and the necessity of the transnational monitoring of system adequacy.

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Enclosure

A Side note: Options of further progress based on the TSOs‘ current power balance

Section 2.3 explains which requirements calculation methods and input data for monitoring system adequacy and the parameters / indicators itself should fulfill in the current and future electricity system. The power balance provided by the German TSOs does not fulfill such requirements to a sufficient degree. For this reason, we have developed a new methodology explained in section 3.

However, the calculation method of the TSOs‘ power balance can be developed further in order to overcome some of its deficiencies. The calculation method described hereafter, for a power balance having residual load as indicator (at the time of annual peak load) could be a considerable improvement compared to the status quo. It would, however, still fall behind the methodology presented and applied in this study. For this reason we would recommend to proceed with a methodology based on a stochastic, cross-border and intertemporal simulation balancing generation and the short-term price-inelastic share of load (cf. section 3.1 to 3.4). Furthermore, we recommend to use such parameters/indicators which describe more precisely the probabilistic character of system adequacy in the current electricity system (cf. section 2.3).

Taking for granted the TSOs‘ current power balance options of further development – mainly with the view to the calculation methodology – relate to the following:

- **Improved consideration of the stochastic characteristics for the availability of conventional generation and intermittent and disposable RES-generation:** In order to record the stochastic independency of outages of conventional power plants in a correct manner, the available conventional generation capacity can be determined as distributive function based on the methodology, the so-called recursive convolution. This is a specific procedure, used for example for dimensioning the demand of control reserve. Stochastically independent outages of conventional power plants and the non-availability of intermittent RES-production can be mutually recorded in the same type of procedure.[1] A correctly chosen process should control which parameters show sufficient stochastic independency as this is a pre-requisite for the application of the convolution method. Stochastic independency can

[1] This methodology was applied in several studies (cf. for example the “dena-Netzstudie I” [13], r2b / Consentec (2010) [14] “Monitoring der Versorgungssicherheit in Österreich” [15]). In this respect the status quo for monitoring does not correspond to the state-of-the-art.

achieved by choosing suitable input-data. The used distribution functions, especially those relating to the availability of RES-production can be estimated on basis of empirical time-series. The quality of this estimation depends on the volume of the data base used. This procedure results in a distribution function of available generation capacity as far as the static preconditions are met.

- **Establishing a consistent level of adequacy in relation to the reliable available capacity:** The TSOs'current power balance does not allow to allocate a consistent and unambiguous level of adequacy to the reliable available capacity. Hence, it is not possible to derive how likely it is that the determined reliable available capacity is actually available. If a distribution function of the available capacity for the total generation collective is calculated, as described in the previous item, such a distribution function can determine the generation capacity available with a certain probability.

  In the terms of the currently applied indicator (reliable available capacity at the time of annual peak load) the available generation capacity – with a certain probability – can basically be compared with the annual peak load expected.[2]

- **If possible: regional consideration instead of neglecting the cross-border electricity exchange:** The TSOs's current procedure completely neglects the cross-border electricity exchange and thus the realization of the European internal market for electricity as the power balance is exclusively determined on a national level (cf. section 2.3). In the particular case of Germany, this tendsto underestimate the level of system adequacy. Generally, the sum of each national consideration for all countries underestimates the level of system adequacy as portfolio effects considering load, RES-production and outages are neglected.

  Based on TSOs' current national power balance, the cross-border electricity exchange should be considered and generally a transnational power balance instead of a national one be determined. In principle, the method would be the same as described above, however, differing in the fact, that no data of the individual countries are used in order to determine the corresponding distribution function by their own. Instead, the data of the whole region

[2] For this procedure the statistic prerequisites, such as stochastic independency and several samples of the used input data, have to be fulfilled.

have to be used for calculating the corresponding distribution function. However, this approach completely neglects probable restrictions due to cross-border transmission capacities within the region. This tends to overestimate the regional level of system adequacy. The relevance of such an overestimation can be calculated by pre- and parallel investigations. If such a regional consideration is applied, the statistical requirements, as described above, have again to be controlled due to the changed database.