Do variable renewable energies endanger the power system ? – An approach to measure flexibility

Barbara Breitschopf,
Fraunhofer ISI
Competence Center Energy Policies and Markets,
Breslauer Str. 48, 76139 Karlsruhe, Germany,
barbara.breitschopf@isi.fraunhofer.de

Alisa Bäumann
bnNetze GmbH,
Asset Management
Tullastr. 61, 79108 Freiburg, Germany
alisa.baeumann@bnnetze.de

***Abstract*—. Balancing of electricity supply gets more difficult due to increasing shares of volatile renewable energy. Based on hourly solar and wind power generation and load data, hours with the largest deviation between forecasted and actual load and variable renewable energy power generation are identified. The power system's flexibility is measured at the level of the power system's components: generation, cross-border transfers, market and operation. To depict the still available flexibility in critical times at the component level, the actual use of flexibilities in critical hours is compared to the available flexible potential. The results show that most countries dispose of sufficient generation and transmission flexibility as well as of market and operational flexibility.**

***Index Terms* renewable energy, market integration, flexibility, indicator, electricity market.**

I. INTRODUCTION

Concerns regarding climate change, energy security as well as volatile fuel prices have pushed the deployment of renewable energies, especially in the power sector. The generation of power based wind or solar is defined as variable because the output depends on the prevailing environmental conditions [1], which are not fully predictable. Variable and uncertain power generation and load are not new to power systems as conventional resources might fail or load might change unexpectedly. However, variable renewable power generation makes balancing of supply and demand more challenging to achieve [2]. Based on forecasts of load and electricity from wind power and PV plants, the residual load is assessed and the generation capacities are scheduled at the day-ahead market accordingly. As forecasts on wind and solar power generation include some degree of uncertainty, the power system should be flexible to adjust to unexpected changes. For example, a decrease in load while at the same time wind power increases requires a large reduction of conventional generation, which is particularly challenging if the residual demand is low and conventional must-run capacity is high. In addition, a simultaneous increase in demand and decrease in actual wind power (compared to forecasted) requires a steep positive ramp of conventional generation capacities, adjustments at intraday and reserve markets. On the other hand, an increase in wind and especially solar power during peak times might reduce conventional generation. With growing variable renewable energy (vRE) shares, all these mechanisms become increasingly important to integrate successfully renewable energies (RE) into the power system. The objective of this paper is to show which components of the power system are used to adjust to those unexpected changes in load and renewable generation and how much of the system's flexibility is used in critical situations.

First, the paper briefly reviews literature discussing flexibility measures of the power system. Next, it describes the approach and finally displays and discusses the results.

II. REVIEW

Flexibility is defined in terms of ability of a system to deploy its resources to respond to unexpected changes in supply and load [1] within a short time period. Even though high shares of vRE based power generation reduces the employment and profitability of conventional generation options [3], they do not all call for high flexibility needs of the system. For example power from wind resources may even align with energy demand peaks [4,5]. In contrast, the decrease of PV output in evening hours is often synchronized with increasing demand [6] requiring more flexibility of the system. [5] look at the integration of vRE over multiple time scales. Hourly variability is based on frequency and magnitude of hourly ramp events, seasonal variability on relative frequency distributions and inter-annual on average storage and back-up resource. Similar, [5] identify a system's flexibility by its operating ramping and minimum downtime flexibilities. And more specific, [6] conclude that not the ramping capacity but the ramping rates are important flexibility requirements. [7] distinguish between two kind of flexibility: a long-term flexibility to adjust conventional generation technologies to a residual demand which might be decreasing over time but with increasing but scheduled ups and downs over hours. And secondly, a short-term flexibility up to one hour, which arises from short-term deviations between forecasted and actual

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outcomes; they are not scheduled. Thus, sudden changes in the supply-demand-balance, be it an unexpected decline or increase in vRE power generation, or changes in load, challenge the power system's flexibility.

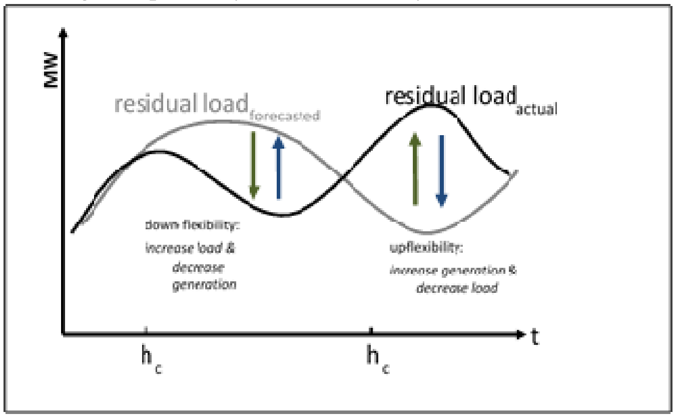

Figure 1. Flexibility needs of the power system

In line with [7], we focus in our analysis on this short-term flexibility, i.e. the unscheduled changes in load and vRE generation within one hour (see Figure 1).

III. APPROACH

A. Critical situations

Flexibility is needed for an electricity generation that depends on vRE [8], but flexibility is not needed all day, only in special situations. Thus, we first identify situations in which especially high flexibility in the system is required. According to our understanding and based on literature [7], critical situations exist, when demand and generation of volatile generation go in opposite directions. The so called long-term flexibility according to [7] encompasses hours with high load and low vRE generation or vice versa, which represent no challenge for the power system when they are scheduled. However, what happens if actual load and generation deviates from the scheduled generation and load? The components of the power system have to react and adjust the schedule to the actual needs. Thus, unexpected changes in load and vRE power generation calls for short-term adjustments of the system. Subsequently, flexibility includes a dynamic component and even seemingly stable situations - from a static point of view - with low vRE power generation and load might call for high flexibility if there are short-term deviations from forecasted and actual residual load (defined as the remaining load when vRE generation is taken into account). Thus, we define critical hours as situations in which short-term adjustments in the power system are highly needed due to large deviations of actual from forecasted load and vRE generation. Thus, there are two critical situations according to Figure 1, which can be depicted in mathematical terms as:

1. ramping up (up-flexibility): $-\Delta$ vRE & $+\Delta$ load [1]
2. down-flexibility: $+\Delta$ vRE & $-\Delta$ load

where $+\Delta \equiv$ *forecasted* $<$ *actual*

$-\Delta \equiv$ *forecasted* $>$ *actual*

In summary, critical hours are situations in which changes of the residual load are the largest, thus, when:

$$\max \left| \Delta \, vRE - \Delta \, load \right|$$

B. Flexibility options

As [3,7,8,9] state, flexibility in the power system can be achieved through different mechanisms. This means, a mismatch between "forecasted" and "actual" could be compensated through quick adjustments in generation, transmission, markets [10] and operation according to [4]:

1. **Flexible generation capacities**: This indicator depicts the technical available flexibility of the system to adjust to short term deviations from scheduled residual load are large. In order to allow an unbiased comparison of different power systems or Member States, the available generation flexibility is quantified by its ramp-up times or part-load capacities (see [9],[5]), are compared to their actual dispatch in critical hours.
2. **Transmission flexibility**: [11] consider transmission as one key element to maintain flexibility. [12] find that higher cross-border transmission opportunities reduce energy system costs associated with increasing vRE. Hence, transmission capacities between countries allow balancing in times of shortfall or surplus of generation or load across borders.
3. **Market flexibility**: According to [11], to maintain an efficient operation of the electricity system under increasing vRE shares, markets have to transact in near real time and in short time increments. The intraday market is such a market instrument. It corrects for forecast errors and adjusts generation or demand to the actual situation in the short-term. Hence, the intraday market serve as a proxy for short-term adjustments potentials and hence is employed to depict the flexibility of the market.
4. **Operational flexibility (reserves)**: After gate closure, there is still the possibility of imbalances. The reserve market provides these balancing capacities for very short-term variations. [12] find that costs of reserve provisions increase with increasing vRE. Therefore, activated reserves are used as proxy for short-term flexibility at the operational level. In addition, the usage of these volumes gives information about the effectiveness of the other flexibility options.

C. Indicators depicting the degree of flexibility used

The "flexibility indicators" show which share of the available flexible capacity is used in the identified critical hours in each flexibility option. Thus, it is the quotient of the value in critical hours (h_c) to the reference value for each system component k:

$$Indicator_{hc,k} = critical\ value_{hc,k} \, / \, reference\ value_{k}$$

To derive the indicator for critical hours, first, we select the top ten critical hours for up-flexibility. In a second step, we select among those ten critical hours, the highest use (value) of the respective flexibility mechanism. So we ensure capturing really the critical situation.

Ideally, the reference value reflects the potentially available flexibility potential of the system's component. However, for practical reasons, we employ either an annual average value

[1] Δ stands for changes between forecasted and actual schedules

or the annual maximum value of each system component as reference value. Table 1 gives a brief overview of the applied reference and critical values.

TABLE I. REFERENCE AND CRITICAL VALUE OF FLEXIBILITY INDICATORS

reference value (denominator) of up/down flexibility	**value in critical hour (hc) (nominator), hourly basis**	
	up-flex.	***down-flex.***
generation flexibility: capacities of ramp-up time <15 minutes., part-load capacities (average GW)	actual used flexible capacities in times of high adjustment needs	actual running capacity in times of minimum residual load)
transmission flexibility (in GW/h): maximum imports or exports/a	actual imports	actual exports
market flexibility (in GW/h): maximum intrada market volume/a	actual intraday volume	
operational flexibility (in GW/h): maximum reserve volume/a	actual used reserve volume	

Note: flex. = flexibility

IV. DATA

Data is obtained from the ENTSO-E Transparency Platform and Power Statistics, market data come from power stock exchanges and additional information is obtained by the country specific TSOs. In addition to missing data or the use of different sources makes comparisons more difficult.

Generation Flexibility.
To derive the reference value, we rely on average annual net generating capacities of each EU country, which includes capacities under maintenance and overhauls, outages and the provision of the system service reserves. Data on unavailable capacities is not available for all EU 28 countries. We define flexible capacities as those capacities that are able to ramp-up within 15 minutes. Regarding down flexibility, we assume that some plants cannot be completely shut down for technical reasons, or without causing high additional costs. Therefore, these plants will be kept running on part-load. These part-load capacities are not identical with must-run capacities, which are defined as "generation facilities that are necessary during certain operating conditions in order to maintain the security of power systems" [13]. Due to data availability issues, we apply average ramp-up times across all countries based on the fuel type of the facility. For ramp-up within 15 minutes we assume a flexible capacity of one third of nuclear, lignite, coal and biomass fired capacities, for part load about 40%.

Transmission Flexibility
To assess transmission flexibility, we rely on cross-border physical flows as they reveal the actual flows in the respective hours. The flows are calculated on a country basis, i.e. the flows of each interconnector per country are summed up. As reference value, we use the maximum recorded cross-border flows within one year. Alternatively, the net transfer capacity (NTC) gives information about the maximum cross border physical flows that are possible due to grid connection, while considering technical restrictions and the reliability margin reserved by the transmission system operator (TSO) to cope with uncertainties. ENTSO-E provided these numbers for the year 2015, but the data set is incomplete. ACER published in its Market Monitoring Report 2016 a cross-zonal benchmark capacity but they are not available for all countries. To ensure a comparable and consistent indicator across countries, we decided to rely on the maximum physical cross-border flow as reference value.

Market flexibility:
With increasing RET-shares, the importance to balance surplus and shortage on short-term market becomes more important for energy security. However, intraday markets differ in their design (e.g. gate closure time, contracts), size and significance. Data is not collectively available at ENTSO-E level or by any other source, but has to be collected from the different regional power markets. In addition, some countries do not have an intraday market others have more than one energy exchange or even have a common market. Finally, data are not publicly available from all power exchanges. As there exists no "limit of market capacity", we apply an artificial flexible capacity as reference value, namely the maximum intraday traded volume across the year. We argue that the market limit is really reached if under a critical situation the maximum hourly volume ever traded is actually traded.

Operational Flexibility
It is defined by the flexibility provided through the secondary and tertiary reserve market. On the ENTSO-E Transparency Platform data sets are available for imbalances, giving information on the price for up and down flexibility and the traded volumes. The overall available volumes for each type of reserve is defined by the TSOs every few months. Depending on how good the other flexibility options balance deviations from scheduled generation and load in critical hours, more or less reserve power has to be activated. Despite the attempt to liberalise the reserve market, there are still a few big players, that highly influence the price. Therefore, the price fails to signal scarcity. Hence, we suggest applying the contracted and activated volumes for the reference and critical values. However, as information of the contracted volumes is not available, we take the maximum of activated reserve volumes within one year as proxy for the available capacity.

V. RESULTS

The results show how much of the flexibility potential of the power system is used in critical times. This is the case if the indicator value is close to one. Fig. 2 and Fig. 3 illustrate how strongly the available flexibility of selected countries is used in critical hours (see Fig. 2 for countries with a high share of vRE and Fig. 3 for countries with a low vRE share - installed vRE capacities in their electricity generation portfolio).

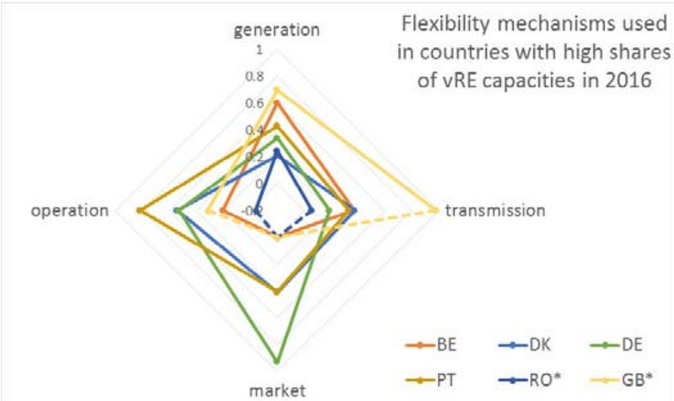

Figure 2. Flexibility indicators of yountries with high vRE shares, 2016

Source: own assessment based on ENTSO-E and power stock exchange data (download 2017). Note: * no intraday market data.

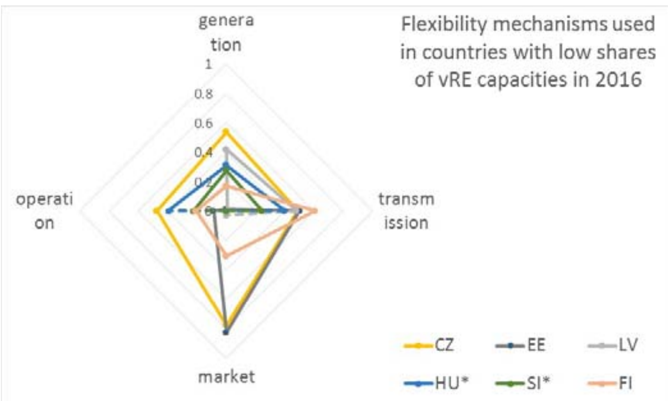

Figure 3. Flexibility indicators of yountries with low vRE shares, 2016

Source: own assessment based on ENTSO-E and power stock exchange data (download 2017). Note: * no intraday market data.

Generation flexibility

Overall, during the critical hours in 2016, all EU Member States have sufficient flexibility in their generation. In general, countries with high shares of nuclear power, lignite or coal based power generation tend to have lower flexibility potential in generation, while gas or oil-fuelled generation have a high ramping potential. Even though a large share of Great Britain's power generation relies on gas, a share of about 0.7 of the available flexible generation is used during its critical hour in 2016. Similar, Belgium disposes of a high share of gas-fuelled generation, and a share of around 0.6 of its flexible generation capacity is running during the critical hour (see Fig. 2). In the lower bound are Estonia with almost zero and Finland with a share of about 0.1 of its flexible generation in operation (see Fig.3). This low share is explained by the fact that Estonia's generation strongly relies on oil-based power generation, which is hardly dispatched in critical hours.

Transmission flexibility

In 2016, the flexibility of the power system with respect to cross-border flows has been underemployed in the EU, except for Great Britain where the import flows reached the maximum value in the critical hour and have certainly mitigated the flexibility pressure on the generation site. In general, large countries in the centre of Europe such as Germany and France or even Italy display high gross border flows. During the critical hours in 2016, Germany's cross border flows were far below the maximum value. This is in contrast to Great Britain, which disposes only of a limited interconnector capacity and hence, its use of transmission capacity is close to one hundred percent in critical hours. Opposite to Great Britain, Romania and, Slovenia display a low use of its cross-border transfers in critical hours. Regarding down-flexibility, the use of cross-border flows (exports) in times of down-flexibility needs is low for most countries, except for Great Britain. This country shows in comparison to its size a low level of export capacities, lower than Portugal, Spain or Slovakia, and in critical hours the critical value is marginally lower that its maximum level.

Market flexibility

In case a country disposes of sufficient generation flexibility, the question arises, how quickly and through which mechanisms will they be dispatched. One option is (intraday) market flexibility. This flexibility indicator is based on the traded intraday volumes in the critical hours compared to the maximum of hourly traded volumes within a year. The closer the indicators to one the more the intraday market serves as a mechanism for adjustments. Data is not available for all EU Member states. For those countries, of which data is available, it becomes evident that in some countries the intraday market plays a significant role. For example, in Germany, Estonia and Czech Republic the traded volume in critical hours was close to the maximum values, while in other countries such as Latvia, Lithuania, or Finland the intraday market seems to be a less used mechanism to regulate unexpected changes in load or generation.

Operational flexibility

Another mechanism to dispatch in short-term remaining available generation capacities is the reserve market. We call this operational flexibility. The activated reserve powers are compared to the yearly maximum in the critical hours per country, which is considered as a proxy for the available volume. In general, the reserve market provides only a small share of the generation capacity as reserves, because the costs of holding reserve power are mostly higher than the average spot market prices of electricity. Thus, under an efficient operation, the reserves are kept to a necessary minimum. In 2016, Portugal and Sweden display high shares. In contrast, Latvia, Estonia, the Netherlands, Belgium and Finland reveal a very low use of their reserve potentials ranging between zero and 0.1.

VI. CONCLUSIONS

Following the starting point of this chapter, stating that increasing vRE shares of wind and solar power make successful balancing of power supply and load more difficult, countries with a high share of vRE might face more challenges integrating vRE. Subsequently, the power system of those countries, in which the share of installed vRE capacities to total generation capacities is the highest, are of special interest of this analysis. Germany, Denmark, Great Britain, Portugal display high vRE shares in decreasing order. In contrast, countries with a low share of vRE such as Latvia and Hungary are supposed to display a small use of flexibility mechanisms. Regarding the flexibility mechanisms of countries with high vRE shares, Germany but also Spain strongly rely on the intraday market to regulate adjustments while Great Britain compensates unexpected changes in load and vRE generation through cross-border transfers. Thus, Great Britain relies on flexible generation capacities of infrastructure of its neighboring countries. Denmark displays a balanced mix of all options whereas flexible generation capacity provides a basis, on which the intraday market also relies on. Countries with lower shares of vRE such as Latvia, Finland or Hungary also display a heterogeneous picture: The intraday market represents a relevant flexibility mechanism for the Czech Republic and Estonia while the networks infrastructure in Finland is a strong pillar for the flexibility of the system. Latvia as well as the Czech Republic dispose of sufficient flexible generation capacities, which might be quickly dispatched through different mechanisms to adjust to varying supply and load.

Overall, in critical hours all countries, those with low and high vRE shares dispose of sufficient flexibility in the system. Countries with low or high vRE shares do not display a special pattern regarding the use of flexibility mechanisms, rather using these mechanisms depends on country characteristics. For example, France has installed only 15% renewable energies but over 60% nuclear power of its capacities. Sweden has a high amount of water reservoirs and therefore a good source to balance forecast differences. On grounds of costs, Great Britain's supply security is mainly based on transmissions as prices in France or the Netherlands are lower than spot prices in the domestic market.

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