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Methodology Paper: Measuring the Flexibility of the Power System

- Approach and results

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Barbara Breitschopf, Alisa Bäumann

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Measuring the Flexibility of the Power System

1. Background

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 (Lannoye et al. 2012), 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 (Cochran et al. 2014). 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 part-load or must-run capacity is high. In addition, a simultaneous increase in demand and decrease in wind power leads to a steep positive ramp. On the other hand, an increase in wind and especially solar power might reduce peak times of conventional generation. Thus, flexibility of the power system becomes more important. Flexibility is defined in terms of ability of a system to deploy its resources to respond to unexpected changes in supply and load (Lannoye et al. 2012). As Cochran et al. (2012) or Bertsch et al. (2016) state, flexibility in the power system can be achieved through different mechanisms, such as changes in market operations, increased transmissions, additions of flexible resources or secured by reserves. Thus, key factors for a flexible system are the availability of flexible capacities on the generation side, high transmission capacities between countries and short-term compensation by intraday trade or balancing through the reserve market.
With growing variable renewable energy (vRE) shares, all these mechanisms become increasingly important to integrate successfully renewable energies (RE) into the power system.

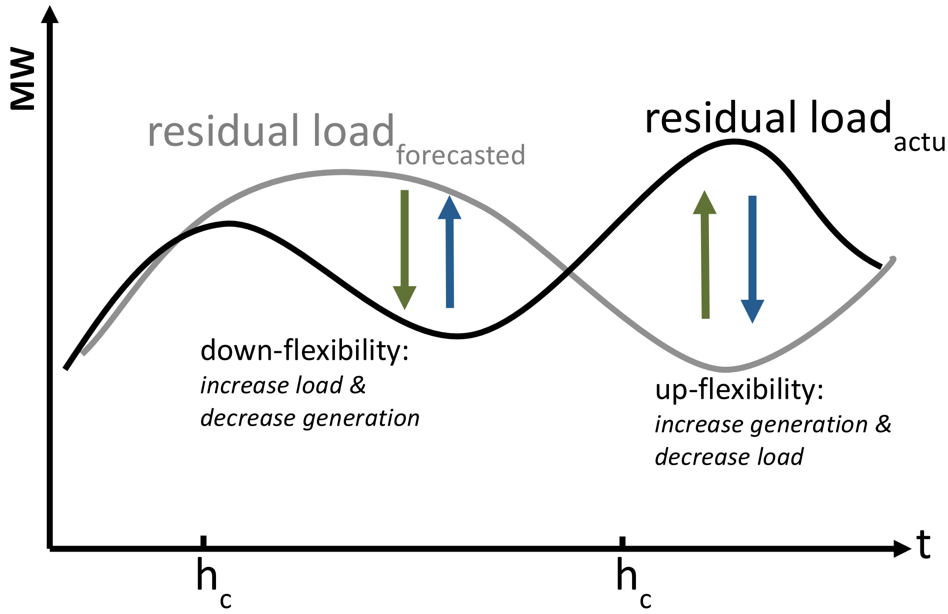
DG Ener has emphasized the need for indicators measuring the actual flexibility of the market (project meeting 29.06.2017) under increasing shares of vRE. In this respect, a set of indicators is elaborated in the following.

2. Approach

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. Even though high shares of vRE based power generation reduces the employment and profitability of conventional generation options (Cochran et al. 2012), they do not necessarily call for high flexibility needs of the system. For example power from wind resources may even align with energy demand peaks (Denny et al. 2017) while the decrease of PV output in evening hours is often synchronized with increasing demand (Koltsaklis et al. 2017). In line with Bertsch et al. (2016) we distinguish between two kinds of flexibility: a long-term flexibility to adjust conventional generation technologies to a residual demand which might be decreasing over time but with increasing scheduled ups and downs over hours. And secondly, a short-term flexibility within one hour, which arises from short-term deviations between forecasted and actual outcomes. 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. We focus our analysis on this short-term flexibility.

To adjust the system to changes in demand and vRE generation, different mechanisms are applicable (Deason 2018; Gonzalez-Salazar et al. 2018), or as Bertsch et al. (2016) states, possible contributions from all parts of the electricity system are required. This means, a mismatch could be adjusted by flexibility options in generation, transmission, markets (Weber 2010) and operation as Denny et al. (2017) summarized in their literature review (see Figure 1). Based on these mechanisms, flexibility indicators are derived and explained in the following.

Figure 1: Flexibility needs of the power system



Source: own depiction. Note: residual load is the difference between load and vRE generation

2.1. When is flexibility needed

Flexibility is crucial and needed for a highly vRE based electricity generation (Deason 2018). Thus, we first identify situations in which high flexibility in the system is required. According to our understanding and based on literature (Bertsch et al. 2016), critical situations exist, when the demand and generation of volatile generation go in opposite directions, that are hours with high loads and low vRE generation or low load and high vRE generation. However, once this generation and load pattern is scheduled and no forecast errors occur, the system needs no further flexibility mechanisms. These capacity provisions are called long-term flexibility according to Bertsch et al. (2016). In opposite to the long-term perspective, we take into account the short-term. We argue that the unexpected changes in load and vRE power generation calls for short-term adjustments of the system. Subsequently, flexibility includes a dynamic component and even - from a static point of view - stable situations with low vRE power generation and load might call for high flexibility if there are short-term deviations from forecasted and actual residual load[1].

Therefore, we define critical hours as situations when short-term adjustments in the power system are needed due to large differences between forecasted and actual load and forecasted and actual vRE generation. Thus, there are two situations, which are typically critical (see Figure 2):

1. ramping up (up-flexibility):

-Δ vRE & +Δ load

where *-Δ vRE ≡ vRE forecasted > vRE actual*
+Δ load ≡ load forecasted < load actual[2]

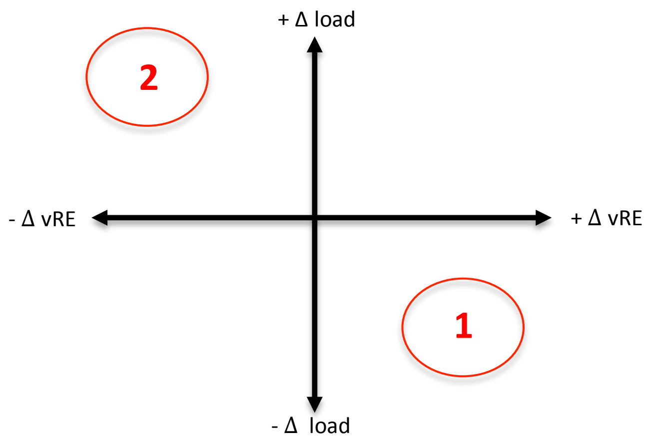
2. down-flexibility:

+Δ vRE & -Δ load

where +Δ vRE ≡ *vRE forecasted < vRE actual*
-Δ load ≡ *load forecasted > load actual*

In summary, critical hours (h_c) are situations in which the deviation │Δ vRE - Δ load│ is the largest.

Figure 2: Definition of critical situations



Note: Δ stands for changes between forecasted and actual schedules

In the first case (up-flexibility), additional power or a reduction of load is needed. The second case, called down-flexibility, entails curtailing especially of

[1] Defined as difference between load and vRE based electricity generation, i.e. remaining load

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

renewable power or an increase of load. This might reduce sustainability and cost efficiency of generation, but it is feasible in most of the situations. In contrast, ramping up within a short time is more critical due to technical requirements, thus, up-flexibility is of particular interest.

In the following, the up-flexibility in the power system is analysed based on generation, transmission and balancing, and down-flexibility is included in generation and transmission options.

2.2. Selection of critical hours

In a first step the top then critical hours of up-flexibility (highest values: -Δ vRE & +Δ load) and bottom ten of down-flexibility (lowest values: +Δ vRE & -Δ load) within one year are identified. They build the basis for the calculations as they provide the day and hour of the critical situations. In a next step, we assess the use of the flexibility mechanisms in each of the top ten and bottom ten critical hours. Given the use of the four options in each of the ten critical hours, we select among the ten critical hours the hour in which the flexibility option is the most used, i.e. the maximum (minimum) value of each option.

2.3. Flexibility mechanisms

To depict the power system flexibility we rely on four flexibility mechanisms[3] of the power system:

1. **Flexible generation capacities**: This indicator depicts the technical available flexibility of the generation side to adjust to a situation where generation is smaller than actual load or vice versa.

2. **Transmission capacities**: This indicator analyses the possible cross-border flows (ex/imports of electricity) between countries, which allow balancing in times of shortfall or surplus generation.

3. **Market flexibility (intraday)**: With increasing RET-shares, the importance to balance surplus and shortage on short-term is crucial for energy costs and the system security. Hence, the intraday traded volumes are analysed to depict the actual 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 when the overall market volume is finally given. The usage of reserves provides information about the effectiveness of the other flexibility options and still indicates how much more is finally available in the respective critical hours.

2.4. The four flexibility indicators

[3] These mechanisms are not necessarily independent, e.g. flexible generation capacities will be active in intraday and reserve markets.

The flexibility indicators display the share of used flexibility to available flexibility of each flexibility mechanism. That is, it shows the relation of the value in critical hours to a reference value, which represents the available flexibility under the respective flexibility option.

Table 1: Flexibility indicators: Reference value and critical value

Reference value (denominator) in the respective year (t)	Value in critical hour (h_c) (nominator)	
	Up-flexibility in h_c	Down-flexibility in h_c
Generation flexibility (average GW): capacities of ramp-up time <15 min part-load capacity	actual used capacities (hourly) in times of high adjustment needs	actual used capacities(hourly) in times of minimum residual load
Transmission flexibility (in GW/h): Max. import capacity in t Max. export capacity in t	actual imports	actual exports
Market flexibility (in GW/h): Max. intraday volume in t	traded intraday volume	
Operational flexibility (in GW/h): Max. reserve volume in t	activated reserve volume	

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" (Didsayabutra et al. 2002). Both, the ramp-up time and part-load capacities depend on the technology, degree or modernisation and fuel type of the generation facility. But detailed country specific technical information on each generation facility to determine ramp-up times and part-load capacities is not available. Therefore, we apply averages 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, to the maximum, there are further options for a reference value. For example, 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. However, the data set is incomplete, the numbers given are often smaller than the actual physical flows and NTC values are reported as forecasted day-ahead transfer capacities after 2015. Furthermore, ACER published in its Market Monitoring Report 2016 a cross-zonal benchmark capacity. This capacity is based on several assumptions such as *a)* cross-zonal capacity is only limited by cross-zonal network elements and *b)* the capacity of these network elements is fully available for cross-zonal exchanges. Unfortunately, these benchmark capacities are neither available for all EU countries, nor for the connected neighbouring non-EU countries. In addition, some actually traded volumes exceed these capacities as well. 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 EU-level source, but has to be collected from the different regional power markets. In addition, some countries do not have an intraday market e.g. Malta, Cyprus and Greece, while in other countries more than one energy exchange (e.g. UK) operates. Some EU countries combined their intraday markets, as for example France, Germany and Austria. Due to this market-coupling and cross-border trade, reported numbers of these countries differ, i.e. include exported and imported volumes. When the buy volumes exceed the sell volumes for a specific hour, there has been net import of electricity. If it is the other way around with sell volumes exceeding buy volumes, there is a net export from this country towards its neighbouring countries. In this case, the smaller value will be taken, as it only displays the volumes traded within one country. Overall, data are not publicly available from all 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 reached if under a critical situation the maximum hourly volume ever traded is actually traded. Finally, we look at the up-flexibility, as the intraday market depicts volumes that are traded to meet the short-term demand.

Operational Flexibility

It is defined by the flexibility provided through the 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 can 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. But data on the general, contracted reserve capacity per country is not available. The data on "volumes of contracted balancing reserves" indicate the overall available reserve volumes, but do not include data for individual European countries. Subsequently we take the maximum of activated reserve volumes within one year as proxy for the available capacity. Additionally, not all EU countries do have a reserve market. Finally, primary balancing power is not included into the imbalances, as these reserves are automatically activated to stabilize the grid within 30 seconds and only a performance price is considered, which is included in the network charges paid by the consumer. The secondary and tertiary balancing power are considered with their commodity price. For these two balancing powers, the retained volumes as well as the activated volumes (merit-order) are covered.

2.5. Data

Data is obtained from the ENTSO_E Transparency Platform and the country specific TSO pages and regional power exchanges. Data availability is limited and not all EU countries have intraday or balancing. In addition, generation data are not completely available for all countries.

Results

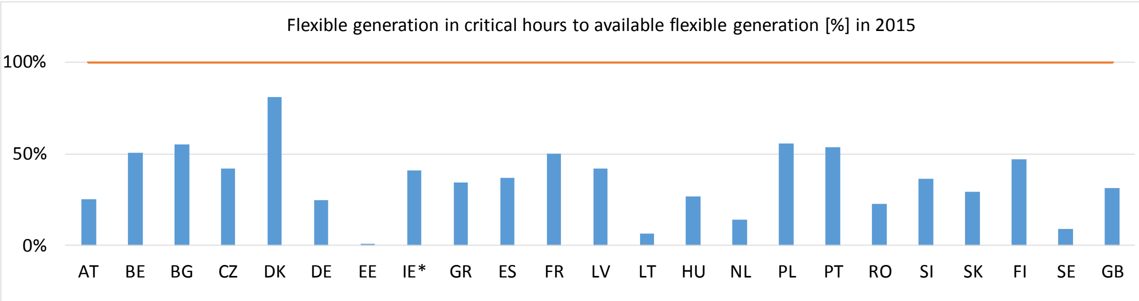
In the following, the results depicted in this overview display up-flexibility indicators for all four flexibility mechanisms and down-flexibility indicators for generation and transmission. Due to restriction in data availability, no critical hours are defined for Malta, Cyprus and Luxemburg, while for Czech Republic, Italy and Croatia critical hours are defined on the basis of incomplete data sets and deviations in load. In addition, data on actual generation, transmission, intraday and reserve market are limited from case to case for several EU countries. These limitations are indicated at the respective paragraph or figure.

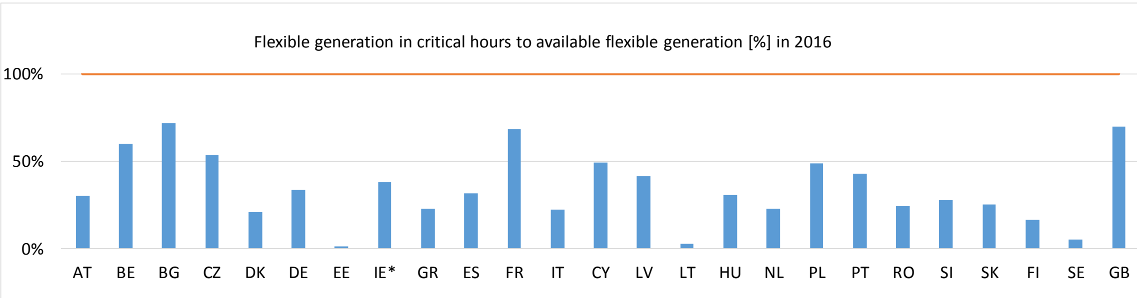
Generation flexibility

To measure up-flexibility, we calculate the share of the used generation in critical hours to technical available flexible generation. Thus, for every EU-member conventional energy generation technologies are taken into account and the up-flexibility based on the ramp-up time is assessed and compared to the actual running capacities in the critical hours. The results are depicted in Figure 3. The blue bars show the relation of running capacity to available flexible capacity, i.e. the percentage of used capacity. The closer the bar is to the 100% line (orange line) the smaller is the remaining flexibility potential for the system.

Overall, all EU Member States have sufficient flexibility in their generation. In 2015, Denmark used up to 80% of the available flexible generation while it went down to about 20% in 2016. Great Britain used about 70% of the available flexible generation in 2016, which was mainly based on gas fuelled generation. Similar France, Bulgaria and Poland display high shares. In France, the high share of nuclear power does not support the flexibility of a system while in Bulgaria and Poland the use of lignite or coal limits flexibility in power generation. In the lower bound are Estonia, Lithuania and Sweden, which used 0% to 5% (2016) of their available capacities. This low share is explained by the fact that in Estonia and Lithuania supply relies on gas or oil and both are very flexible but hardly used in critical hours.

Figure 3: Generation flexibility in critical hours 2015 and 2016





Source: own assessment based on ENTSO-E data downloaded 9/2017. Note: no data for HR,CY, ,LU, MT

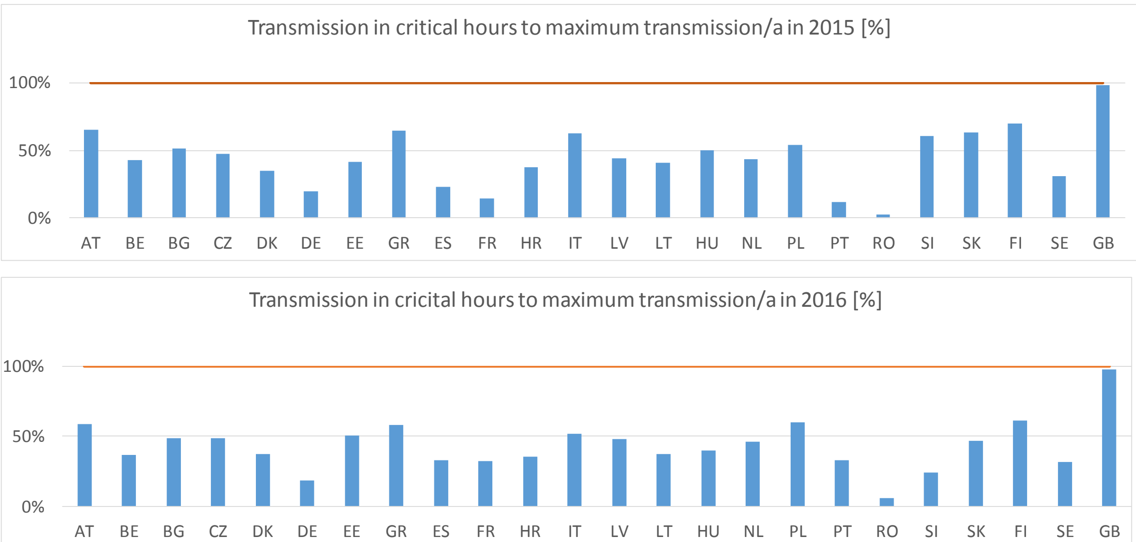
In hours of down flexibility, the part-load capacities of conventional power plants define the lowest possible threshold of energy generation. Overall, in countries where nuclear power generation or lignite based power generation plays a role (e.g. France), the situation is more critical than in countries with high gas or oil fuelled power generation (e.g. Estonia, Latvia, Lithuania and Cyprus). However, the approach of selecting critical situation for down-flexibility in generation differs from that for up-flexibility: critical situations for down-flexibility (in generation only) are not the changes in residual load but hours in which residual load is minimum. Given our approach, we see that in situations where forecasted load is significantly higher and forecasted vRE generation lower than actuals, the conventional generation capacity of only a few countries is close to the part-load capacity.

Transmission flexibility

To illustrate the flexibility that is available through cross-border exchanges, the import flows in critical hours are compared to the maximum import flows on an hourly basis within the respective year. Figure 4 shows the up-flexibility (imports) needed in critical hours during 2015 and 2016. The closer the bars to the 100% line (orange line), the more available flexibility has been used in the critical hours, i.e. the more severe the situation was.

In 2015 and 2016, the flexibility of the power system with respect to transmission has been underemployed in the EU, except for Great Britain where the import flows reached the maximum value in the critical hour. EU-wide, on average between 40%- 45% of the yearly maximum values were used for up-flexibility in extreme situations. Large countries such as Germany, France and Italy display high gross border flows. However, during their critical hours, their cross border flows were far below the maximum values. Thus, they have still a large potential for up-flexibility. Smaller countries operate at a lower import level but display similar flexibility reserves. Romania and Portugal used almost zero transfer capacities during the analyzed critical hours.

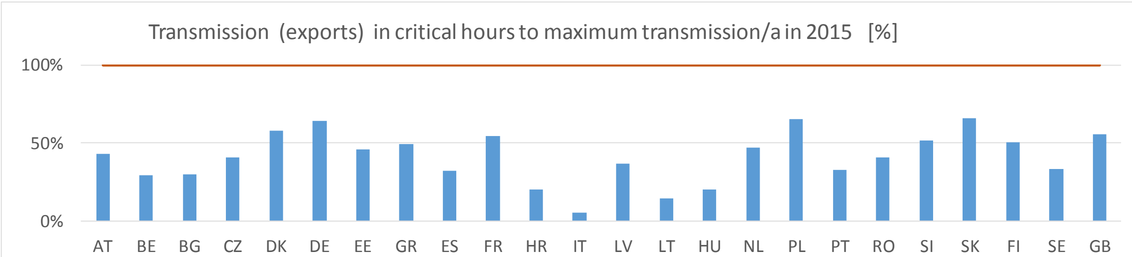
Figure 4: Transmission up-flexibility in critical hours 2015 and 2016

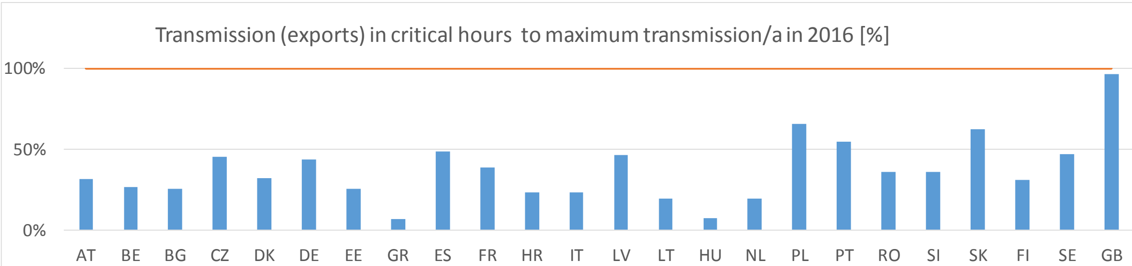


Source: own assessment based on ENTSO-E data downloaded 10/2017. Note: no data for IE, MT, LU and CY

The share of aggregated electricity exports per country in critical hours to the maximum export capacity is employed to depict the down-flexibility in transmission. During critical hours the use of cross-border flows (exports) is low for most countries, and has hardly changed between 2015 and 2016. Great Britain shows in comparison to its size a lower export level (reference value) than Portugal, Spain or Slovakia. In addition, in critical hours Great Britain's export level is marginally lower. This fact explains its high indicator value in Figure 5.

Figure 5: Transmission down-flexibility in critical hours 2015 and 2016



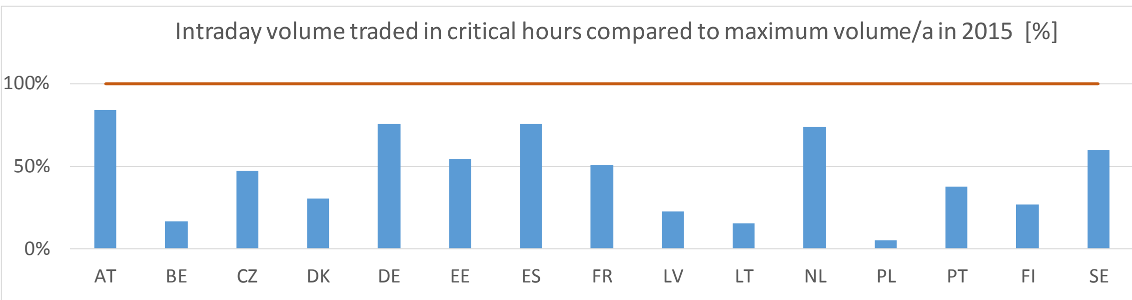


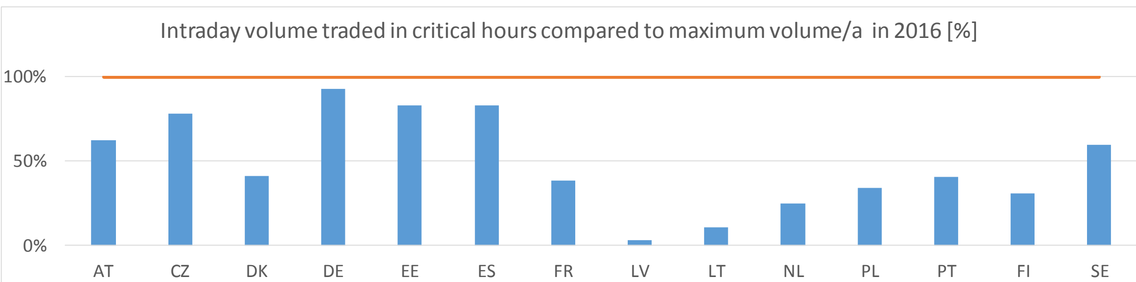
Source: own assessment based on ENTSO-E data. Note: no data for IE, MT, LU and CY

Market flexibility

Market flexibility is based on the traded intraday volumes as depicted in Figure 6. The bars (blue) show the traded intraday volume in the critical hours compared to the maximum of hourly traded volumes within a year. The closer the blue bar to the orange line (100% line) the more the intraday market served as a mechanism for adjustments. Data is not available for all EU Member states. But for those countries, of which data is available, it becomes clear that in some countries the intraday market seems to play a significant role. For example, in Germany and Spain, the traded volume in critical hours was close to the maximum values (2016) while in other countries such as Latvia, Lithuania, or Poland the intraday market seems to be less needed to compensate unexpected changes in load or generation.

Figure 6: Market flexibility in critical hours in 2015 and 2016



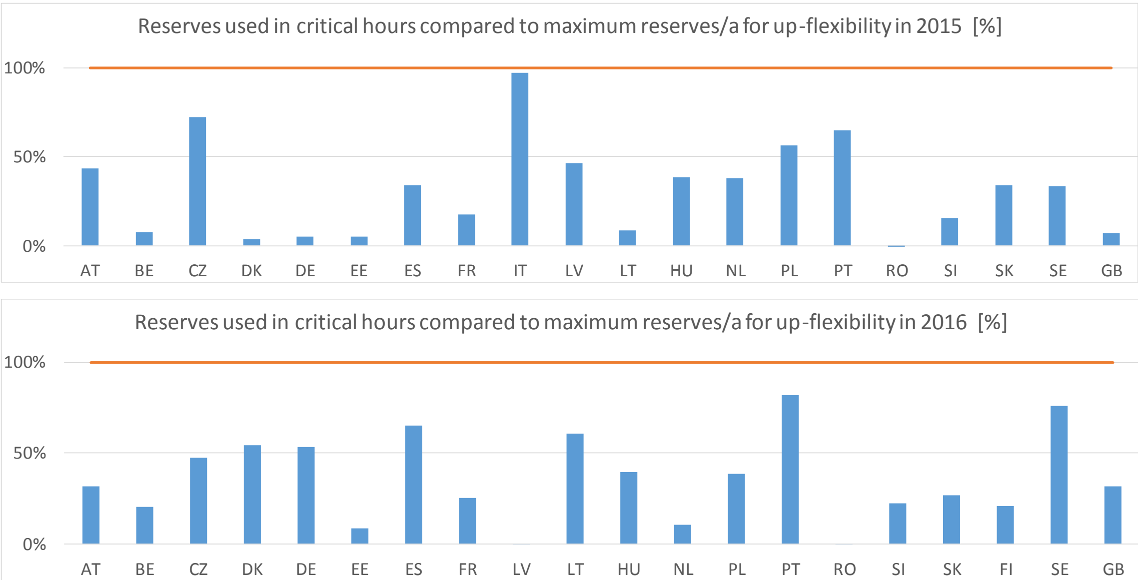


Source: own assessment based on data of power exchanges downloaded 11/2017. Note: no data for IE, MT, LU, CY, BG, GR, HR, IT, HU, RO, SI, SK, GB; AT and DE have a common market, but different critical hours. In ES and PT maximum values are based on the analysed critical hours.

Operational flexibility

Operational flexibility is represented by the reserve market. Here the activated reserves of power are compared to the yearly maximum in the critical hours per country, which is considered as a proxy for the available volume. The bars in Figure 7 depict the share of actual activated reserves in the critical hours to the available volume. The closer the bars to the orange line (100% line) the more the system relies on the operational flexibility potential in critical situations.

Figure 7: Operational flexibility in critical hours 2015 and 2016



Source: own assessment based on ENTSO-E data downloaded 10/2017. Note: no data for BG, GR, IE, HR, MT and CY, no data for IT in 2016. Luxembourg is included in Germany reserves.

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 electricity prices. Thus, there is a strong incentive to keep the use of reserves at minimum.

For 2015, on average almost 30% of the maximum possible reserve power was used during critical hours, but it varies strongly among countries. For example, Germany relied on about 5% (2015) of the operational reserves in the critical hour. However, it cannot be concluded that the contracted reserve volume has to be cut down, because unexpected outages of conventional generation capacities or network problems (in addition to critical hours defined by this report) are still potential challenges of the power system.

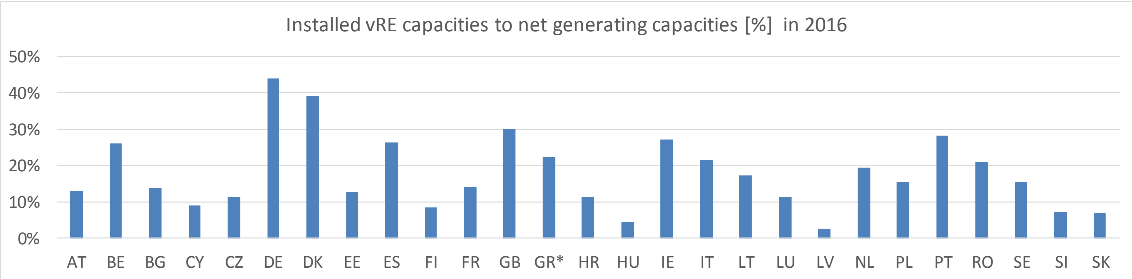
Spain, Sweden and the UK have the highest reserve volumes but at the same time, these countries do not activate even half of their potential in the analyzed critical hour. Italy is close to its maximum annual capacity in its critical hours. Romania is displaying a contrary picture, as the actual used reserve capacity is negative while still having positive potential. One explanation would be that with traded volumes at a kind of intraday market Romania overbalanced the forecast error and therefore has to rebalance with the reserve power.

In 2016, Portugal, Sweden, Spain and Lithuania display high shares. In contrast, Latvia, Estonia and the Netherlands reveal a very low use of their reserve potentials ranging between 0% and 10%. For Romania, the same situation applies as the year before. Even with a demand for up regulation, the actual used reserve power is negative. This analysis is limited to 20 EU Member States due to missing data.

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 higher 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 (see Figure 8). In contrast, countries with a low share of vRE such as Latvia and Hungary are supposed to display a small use of flexibility mechanisms.

Figure 8: Share of volatile renewable energies (installed capacities) in 2016

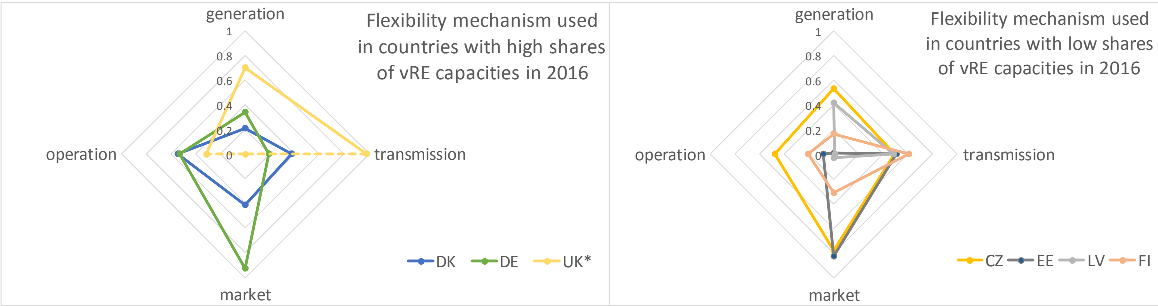


Source: own assessment based on ENTSO-E data (download 1/2018). Note: * data from 2015

Regarding the flexibility mechanisms of countries with high vRE shares, Germany but also Spain strongly rely on the intraday market while Great Britain mainly uses transmission and flexible generation capacities at different markets to compensate unexpected changes. Denmark displays a balanced mix of all mechanisms. Countries with lower shares of vRE such as Latvia, Finland or Hungary neither display a homogenous picture: the intraday market represents an important flexibility mechanism for the Czech Republic and Estonia, while Finland relies on transmission; Latvia as well as the Czech Republic use flexible generation capacities for adjustments to changing supply and load.

Overall, in critical hours all countries dispose of sufficient flexibility in the system. Countries with low or high vRE shares do not display a pattern regarding the use of flexibility mechanisms, rather the use of mechanisms depends on a combination of various country specific characteristics. For example, France has only 15% of renewable energies but over 60% of nuclear power; Sweden dispose of a high amount of water reservoirs and therefore of a good source to balance forecast differences; albeit its high share of flexible generation capacities, UK uses mainly the transmission mechanism as prices in France or the Netherlands are lower.

Figure 9: Countries with low and high RES shares in 2016



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

However, a country's system flexibility is closely linked to the existence of regional markets and grid capacity[4]. Further, the (intraday) market flexibility depends on the available capacity provided by the TSO.[5] Thus, neither the system's flexibility nor the components' flexibility are isolated issue, but interdependent.

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[5] https://www.nordpoolgroup.com/TAS/intraday-trading/capacities/

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