Integration of wind and solar power in Europe: Assessment of flexibility requirements

Matthias Huber [a,*], Desislava Dimkova [b], Thomas Hamacher [a]

[a] Institute for Renewable and Sustainable Energy Systems, Technische Universität München, Arcisstr. 21, 80333 Munich, Germany
[b] School of Forest Science and Resource Management, Technische Universität München, Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany

ABSTRACT

Flexibility is the ability of a power system to respond to changes in power demand and generation. Integrating large shares of variable renewable energy sources, in particular wind and solar, can lead to a strong increase of flexibility requirements for the complementary system, traditionally hydrothermal, which has to balance the fluctuations of variable generation. We quantify these flexibility requirements at the operational timescale of 1—12 hours and different spatial scales across Europe. Our results indicate that three major factors determine the ramping flexibility needed in future power systems: the penetration of variable renewables, their mix and the geographic system size. Compared to the variability of load, flexibility requirements increase strongly in systems with combined wind and PV (photovoltaics) contribution of more than 30% of total energy and a share of PV in the renewables mix above 20—30%. In terms of extreme ramps, the flexibility requirements of a geographically large, transnational power system are significantly lower than of smaller regional systems, especially at high wind penetration.

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1. Introduction

Strong drivers like climate change, the scarcity of fossil resources and an increasing public aversion to nuclear power are leading to a transformation of the power system in many world regions. Increasing shares of renewable energy sources, especially wind and solar, are deployed in former hydrothermal systems. Electricity generation from these sources is variable and uncertain, which makes their integration into traditional power systems a challenging task. Uncertainty is problematic because it may result in suboptimal preparation of the system to balance fluctuations from variable generation (VG). Schedules of thermal power plants or storage have to be changed within a short time in order to react, for instance, to unexpected wind picking up or calming down. But even under perfect forecast circumstances, the variability of wind and solar power output stresses system operation in two ways: it can cause balancing resources to cycle more frequently and may generate ramps of extreme steepness or duration. In order to meet these challenges, the power system is required to be flexible.

Ma et al. [1] define a power system to be flexible if it can cope with uncertainty and variability in demand and generation to maintain system reliability at reasonable additional costs. Flexible power plants, storage, integrated demand-side management (DSM) as well as power sector coupling to heat can provide the power system with flexibility [2,3]. Additionally, geographic dispersion of generators and the extension of interconnections can lead to reduced variability [4]. Insufficient flexibility may limit the share of variable renewable generation a power system can accommodate. It is thus of major importance to understand and quantify upcoming flexibility requirements in order to optimally prepare the system. In this paper, we quantify the flexibility requirements of VG arising from its variability.

The topic and the term "flexibility requirements" came into discussion very shortly in articles focusing on finding metrics for flexibility [1,5–7]. The latter formulated a flexibility trinity of ramp rate, power and energy. Another first attempt to categorize flexibility requirements was conducted by [8], which proposes a qualitative framework for measuring a system's flexibility needs in terms of three metrics: ramp magnitude, ramp frequency and response time. Here we focus on the magnitude and frequency of net load ramps of given duration that have to be balanced by the complementary system as illustrated in Fig. 1.

Besides discussing appropriate metrics for flexibility, some research has been done on describing the flexibility requirements of special power systems, for example, requirements in Ireland

* Corresponding author. Tel.: +49 89 289 23972.
E-mail address: matthias.huber@tum.de (M. Huber).
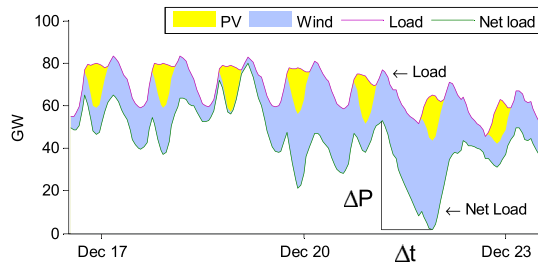
Fig. 1. Illustration of net load ramps in a power system with high shares of wind and solar power. (Adapted from Ref. [9]).

were analyzed in Ref. [10]. In case studies upscaling real wind power data for several European and US regions, Holttinen et al. [11] show that high penetration of wind power can increase the magnitude of extreme net load ramps and change their time of occurrence. The above-mentioned studies focus on the impacts of large wind shares on power systems. The variability of photovoltaics (PV) has been studied mostly for individual sites [4]. In this work, we analyze the flexibility requirements of large-scale penetration of both wind and PV and adopt a comparative perspective.

The temporal dimension of ramp requirements is characterized in Ref. [12] by means of a so-called ramp envelope which bounds the magnitude of ramps over a given timescale with a certain probability. In Ref. [10], the importance of the considered time horizon is discussed and changes in wind power production in Ireland are analyzed on timescales ranging from 15 minutes to 9 hours. In Ref. [13], flexibility requirements for the German power system are analyzed in scenarios about the future development of PV and wind installations. This analysis covers different timescales ranging from 1 to 20 hours and shows that ramp rates in Germany will increase strongly in the next years. The outlined studies show the importance of the topic as well as the additional research that is needed.

We use several of the above-mentioned methods and analyze flexibility requirements at timescales from 1 to 12 hours for power systems with projected high shares of wind and PV. Compared to previous work, we extend the analysis to 27 European countries and statistically show basic properties that are common to most systems depending on the share of renewable energy in the system and the wind/PV mix. We find that the wind/PV mix is equally important for the ramp requirements as it was shown to be for system costs [14] and the minimal mismatch between renewable generation and load [15,16]. Still, the share of wind/PV and their mix do not explain all the variability in the system; differences between countries remain. In order to understand and explain those differences, we investigate additional system parameters: the geographical system size as well as the wind and solar resource potential in terms of full load hours (FLH). By that, we extend the methods described above and make the first move to a generalized characterization of future flexibility requirements in power systems. To the best of our knowledge, such a general analysis of upcoming flexibility requirements arising from variable generation in power systems has not been conducted before.

Our analyzed region is Europe, however, the framework for the analysis can be applied to any other world region. The results provide a deeper understanding of the occurring ramp rates in many power systems and allow, on the one hand, for designing the variable system in such a way as to minimize problems in the controllable system or, if this is not possible, the analysis allows system planners to foresee upcoming requirements and adapt the controllable system in an adequate way.

The remainder of the paper is organized as follows: In Section 2 we start with a description and validation of the modeled data for wind and PV power generation. We then analyze in Section 3 the influence of the wind/PV mix as well as the share of variable generation on the flexibility requirements. Additional influencing parameters that explain differences between power systems are analyzed in more detail in Section 4. After identifying system size as an important property, in Section 5 we focus on the advantages that could be realized through a stronger cooperation among countries in Europe. Finally, Section 6 concludes the paper by summarizing the major findings of the research and giving an outlook on the meaning of the results for system planners as well as on future research directions.

2. Methodology

2.1. Model data and validation

The analysis in this paper is carried out using modeled time series of onshore wind and solar PV power production for the period 2001–2011 in 27 countries in Europe (the European Union members, with the exception of the isolated power systems of Malta and Cyprus, together with Norway and Switzerland). The time series are based on NASA reanalysis data [17], which consists of hourly values of wind speed and solar irradiance at a spatial resolution of 0.5° E/W and 0.66° N/S for the whole world. The weather data for each spatial grid cell was converted by Ref. [18] into wind and PV power production time series. Our analysis explicitly excludes offshore wind power, as we want to have a unified framework to compare countries and regions but not all countries have the possibility to install offshore power. In addition, historical offshore data is only rarely available, thus validation of models is difficult and it is not clear whether offshore power will be exploited on a large scale in Europe.

From the time series for wind and solar power in the grid cells, a weighted average is built to obtain aggregated power production at the regional and country level. The weighting factor for each cell is proportional to the resource potential in terms of wind speeds or solar radiation (energy density) − more capacity is assumed to be installed on sites with higher energy density as this is cost-efficient. The weights are generated separately for wind and PV and for each modeled country or region as follows: The grid cell with the lowest density is assigned a weight of zero and the one with the highest density is assigned the difference between the maximum and the minimum energy density values of all cells in the respective country. A linear interpolation between those two weighting factors is applied to obtain weights for the grid cells with wind speeds or solar radiation in between. Finally, the weighted average electricity generation of all cells in each hour is normalized with respect to installed capacity, i.e. it is converted into hourly wind and PV capacity factors in the interval [0, 1] [18]. Fig. 2 shows the average annual full load hours of the thus obtained wind and PV power generation in the analyzed countries.

For our investigations, the most important factor is not the power production profile but the power ramps, or gradients, occurring over different time horizons. A power ramp $\Delta_h P$ is defined as the change of power in a given time interval of h hours:

$$\Delta_h P(t) = P(t) - P(t-h) \tag{1}$$

where $t = \{h+1,...,8760\}$, $P(t)$ is the wind or PV power production in a spatial unit (country or region) at time t. In order to validate the simulated power output profiles, we compare the frequency distributions of hourly ramps of simulated wind and PV power with respective data from the transmission system operators (TSO) in
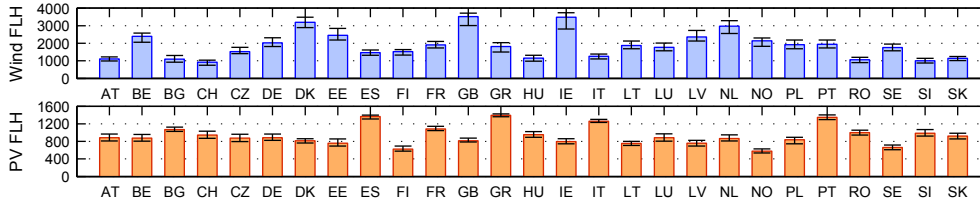
Fig. 2. Average onshore wind and solar PV full load hours per year over the period 2001–2011 as well as their range.

Germany [19] and also with actual wind feed-in data for Ireland [20,21]. As Fig. 3 shows, the model data reproduces very closely the actual ramp behavior both for wind and solar power output.

2.2. Scenarios for wind and PV development and resulting net load

We use the data described above to generate scenarios for future net load, i.e. load minus generation from variable renewables, particularly onshore wind and solar PV. Net load ramps are chosen as a measure of the flexibility requirements of power systems since every change in net load has to be balanced by flexible resources such as dispatchable power plants, storage or responsive loads in order to maintain system stability.

Hourly load profiles for the analyzed countries come from Ref. [22]. Load data for the year 2011 is used in all scenarios to isolate the impact of wind and PV on the variability of net load. A small number of hourly load ramps which lie more than five standard deviations below or above the mean in the original load ramp series are considered outliers and smoothed out in the time series (0.007% of all data points). Annual electricity consumption is assumed to remain at the level reached in 2007.

Electricity generation from wind and PV is calculated by multiplying the hourly capacity factors, obtained from the weather data, with installed wind and PV capacities which are varied in scenarios. The VG capacities are a function of the total contribution of wind and solar energy to annual electricity consumption α and the share of PV in the wind/PV energy mix β. The definitions for α and β are adopted from other studies focusing on the capacity or storage requirements in power systems with high shares of PV and wind power ([16,23,24] use the same or similar methods).

$$\alpha = \frac{\sum_{t=1}^{t=8760} P_{wind}(t) + \sum_{t=1}^{t=8760} P_{PV}(t)}{D} \qquad (2)$$

$$\beta = \frac{\sum_{t=1}^{t=8760} P_{PV}(t)}{\sum_{t=1}^{t=8760} P_{wind}(t) + \sum_{t=1}^{t=8760} P_{PV}(t)} \qquad (3)$$

where $P(t)$ is hourly power output at time t and D is annual demand.

In each country, the net load ramp rates are a linear combination of the ramp rates of load, wind and solar power:

$$\Delta_h NL(t) = \Delta_h L(t) - \frac{\alpha\beta D}{8760\mu_W}\Delta_h W(t) - \frac{\alpha(1-\beta)D}{8760\mu_{PV}}\Delta_h PV(t) \qquad (4)$$

where $\Delta_h(\cdot)(t)$ is defined in Eq. (1), NL is net load, L is hourly consumer load, D is annual electricity demand, $\{W, PV\} \in [0,1]$ is wind and PV power normalized to installed capacity, and μ_W, μ_{PV} is average power over one year. The occurring ramps are all calculated relative to the peak load in each country to allow for comparison across regions. Peak load is interpreted as an indicator of system size because conventional power plant fleets are traditionally sized to meet the annual demand peak with a reserve margin for accommodating outages and extreme load events.

Thus, the system flexibility requirements posed by VG are determined in the model by the following factors:

- the VG penetration level α and the wind/PV mix β as choice variables resulting from policy and investment decisions;
- the ramp behavior of load and the inherent ramp properties of wind and PV power. These properties are determined by geographical location, generator placement and system size, and will be described by means of frequency and temporal ramp distributions in Section 3;
- the correlation between the load and the VG gradients as well as between wind and PV ramps. Load and VG ramping up or down at the same time counterbalance one another, whereas wind and PV power ramps in the same direction add up to increase the system balancing requirements.

The combined energy penetration of wind and PV (α) that is considered is 10%, 30%, 50% and 70% of annual electricity demand. As there are other renewable energy technologies such as hydropower, biomass and geothermal that can be deployed in addition, a share of 70% of wind and PV can be interpreted as a fully renewable power system. At each penetration level, the share of PV β is set to 20%, 40% and 60%.
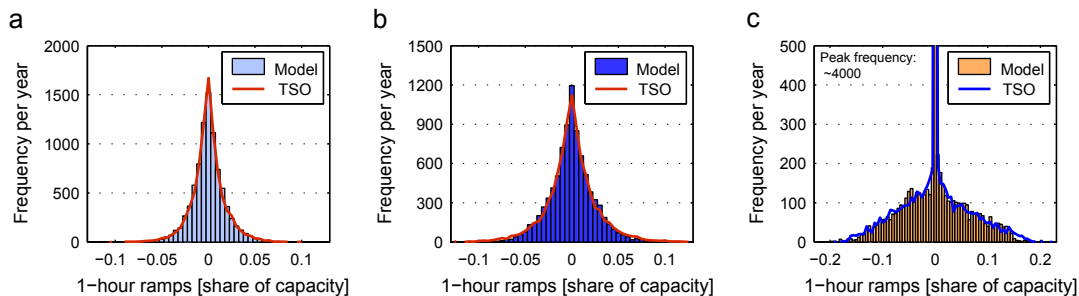

Fig. 3. Frequency distributions of hourly ramps of simulated and actual power production: (a) Wind 2011, Germany, (b) Wind 2010, Ireland, and (c) PV 2011, Germany. Wind and PV power is normalized with respect to installed capacity.

After showing the effects of different levels of VG penetration, we will focus on the 50% scenario for further analysis. A 50% wind/PV share is discussed as an intermediate target in 2030 on Europe's way toward a fully renewable power system [25]. A further argument for having a closer look at that scenario is that our research showed that renewable integration becomes especially challenging in terms of ramps at that share.

In our scenarios, we do not cut off excess energy; the residual load can thus rise from negative to the maximum load leading to a ramp of more than one. A ramp of one means that all controllable resources, except the capacity reserves, are required to provide full load in the specific time frame.

An aggregated European net load is calculated from the country time series as follows: a VG penetration target α and a wind/PV mix β are selected for Europe as a whole and this α/β combination is assigned to each country making up the European power system. Unrestricted electricity transport is assumed between the countries. An alternative capacity configuration was analyzed which minimizes the installed wind and PV capacities in Europe by optimally allocating capacity to the countries with the highest resource potential. However, the effect of the different capacity allocations on the variability of net load was found to be small compared to the impact of the wind/PV mix [21] and we therefore show the results only for the configuration in which the same shares of wind and PV generation are assumed for each country.

It should be noted that our analysis focuses on flexibility requirements in certain scenarios about future development of wind and PV power capacities. Changes in the net load caused by DSM or storage are not modeled as they are already seen as a countermeasure for the variability of renewables, i.e. as part of the flexibility of the residual system.

2.3. Limitations of scenario modeling

The model captures very well the variability of the system at current level of wind and PV penetration in the validation countries. Still, the remaining question is whether the scenarios for net load are scalable for future projections of variable generation or whether there are upcoming effects that would change the outcome. The following effects are identified to have influence on the ramping requirements from further integration of variable generation, i.e. wind and solar:

- Variability of wind may decrease as more turbines get installed but there may be a saturation effect [11].
- Climate change might lead to more extreme weather events. Still, it is unclear if this has any effects on ramping requirements [26].
- Improved wind turbines could be deployed. The effects are not predictable, however, as the enormous ramping requirements challenge the system, wind turbine producers might have incentives to develop turbines with "flatter" power curves.
- Load might change as well: People's work and leisure rhythm, a structural change of the economies and upcoming flexible load and power autonomy of household and industry can also have influence on flexibility requirements in the public power system [27].

To summarize, there are several changes in the behavior of wind and solar generation on the horizon, but most are likely to have low influence or their effects are at present not quantifiable. Overall, the flexibility requirements will be lower than suggested in this paper as new technologies and an optimized placement of generators could reduce variability.

3. The wind/PV mix as determining factor for system flexibility requirements

In this section, we identify the total share of wind and PV in electricity consumption α combined with the share of PV in the VG mix β as determining factors for ramp requirements in future power systems. We first introduce the ramp properties of the individual time series: load, wind and PV. Then we show 1-hour ramp events of net load in scenarios in order to quantify the ramp requirements from hour to hour resulting from the combined effects of the load and VG time series. Finally, we move to an analysis of longer ramps of duration 2–12 hours, as this is critical due to start-up times of conventional power plants [13].

3.1. Ramp properties of wind and PV generation in Europe

Fig. 3 illustrates the basic shape of the frequency distributions of onshore wind and solar PV power fluctuations. Wind power is characterized by high frequency, low magnitude ramps concentrated around the center of the distribution. The largest ramps occurring are in the range of 6–10% of installed capacity per hour in medium-sized and large European countries, and 11–18% per hour in geographically small countries. About half of all hourly solar power ramps are equal or close to zero because of zero production at night but the distribution has long and heavy tails with ramps reaching 18–25% of capacity per hour in most analyzed countries and up to 12–14% in the Nordic countries. The distribution of load gradients is skewed toward upward ramps, typically reaching extremes of 10–15% of peak load per hour in the analyzed European countries.

On the basis of the frequency and temporal distributions of variable generation ramps, the countries in Europe can be grouped into clusters which have similar wind and PV flexibility requirements in terms of ramp magnitude and frequency: North, Center and South. The load, wind and PV time series have a distinct ramp behavior whose daily and seasonal pattern is shown in Fig. 4 for three different European countries representing those clusters (North: Ireland, Center: Germany, South: Italy).

The first row depicts the hourly gradients of consumer load in each country. On a daily basis, the largest load ramps are the morning rise with duration 2–3 hours and a less prominent evening ramp up when lights and appliances are switched on at the same time. While some differences exist, the same basic load ramp structure appears in all European countries we study. Wind and solar power both follow a diurnal cycle. The diurnal harmonics of surface wind speeds over land have been found to be approximately in phase with those of surface air temperatures which follow the diurnal cycle of solar radiation [28]. The middle row of Fig. 4 shows that although wind power generation is very volatile, it tends to decrease around sunrise and sunset, after which it tends to increase again. This pattern is most prominent in Germany and also other countries in Europe's center whereas countries in Scandinavia and the Southern peninsulas rarely experience large wind power ramps. In terms of frequency of large ramps, wind fluctuations pose the highest flexibility requirements in small Northern countries such as Ireland and Denmark. Regarding PV fluctuations, the frequency of large ramps clearly increases in the North–South direction.

3.2. One-hour net load gradients

The unit commitment process is organized in hourly time periods in many power markets. The frequency and temporal distributions of hourly ramp rates are thus an important measure for short-term flexibility requirements of the power system. The
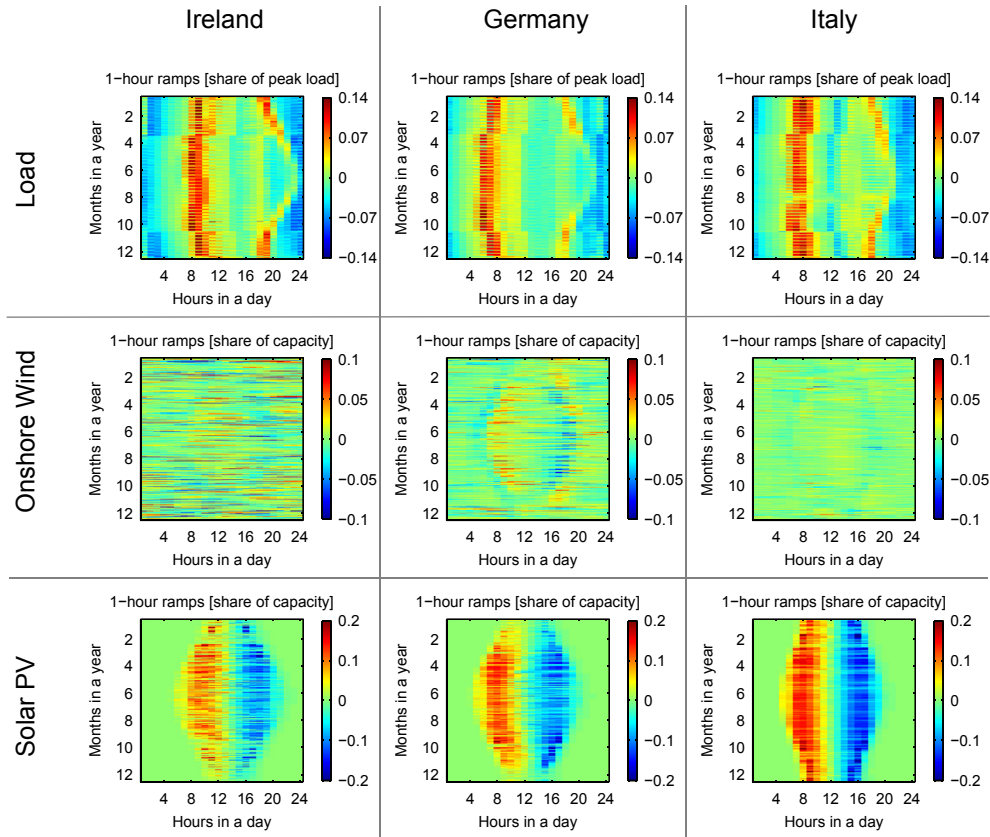
Fig. 4. Temporal distribution of 1-h ramps of load, wind and PV power in Ireland, Germany and Italy for the meteorological year 2011.

impact of those ramps on system operation depends on whether they were forecasted or not. If they are predictable, even slower power plants can be started up early enough to be available exactly when the ramp occurs. However, accurateness of prediction is lower the day ahead and increases when temporally closer to the event [29]. Thus, the power system should be designed in a way to meet those 1-hour gradients by power plants that are already on-line or have a fast start (hydro, gas turbine). Alternative options like storage and DSM can also contribute here. Keeping in mind those impacts on the power system, we proceed with analyzing the net load ramps in scenarios.

As shown in Fig. 5 on the example of Germany, the frequency distributions of hourly net load gradients at $\alpha = 0.5$ are close for the mixes with high share of wind at $\beta = \{0,0.2\}$ and this relationship holds for all analyzed countries. Compared to the load gradient, the frequency of ramps close to zero is reduced nearly by half. Up to a threshold share of 20% PV in the VG mix (in some countries up to 30%), equivalent to 10–15% of annual consumption, the frequency distribution of net load ramps remains of similar shape as for a 100% wind mix. Adding more PV capacity to the system above this threshold results in a large increase in the frequency of high ramps. Depending on country area and full load hours, extreme net load ramps can occur also with high shares of wind in the system. Those extremes are analyzed in Section 4.

Even though countries in Europe have different resource potentials (Fig. 2) and wind and PV ramp properties (Fig. 4), the wind/PV mix has similar effects on the variability of net load. We show this for the example countries Ireland, Germany and Italy, which differ considerably in terms of area as well as wind and PV FLH.

Fig. 6 shows the temporal distribution of the hourly net load ramps for those countries in the scenarios with renewable penetration $\alpha = 0.5$ and shares of PV in the VG mix $\beta = \{0,0.2,0.4\}$. The

plot shows that PV has a far stronger influence on the increase of hourly ramp rates than is the case for wind power. At the 100% wind mix, the hourly net load ramps are distributed randomly but are still mostly dominated by the load ramps. With an increase of PV to 20% ($\beta = 0.2$), the morning rise in load is compensated by PV power generation, which reduces ramps. However, this reduction in the frequency of large net load ramps in the morning is counteracted by an upward ramp pattern in the late afternoon when PV power production slows down and load increases at the same time. With 40% PV ($\beta = 0.4$), the ramps of PV power dominate the net load variability. The frequency of high ramps increases dramatically, with downward net load ramps in the morning and upward in the evening. Ramps of magnitude higher than the morning load rise are maintained over 3–4 consecutive hours in each direction for a significant part of the year in all analyzed European countries.
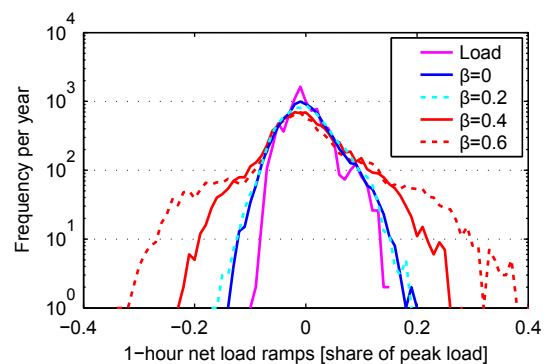

Fig. 5. Frequency distribution of 1-h net load ramps for different shares of PV in the wind/PV mix β at 50% variable generation penetration in Germany, 2011.
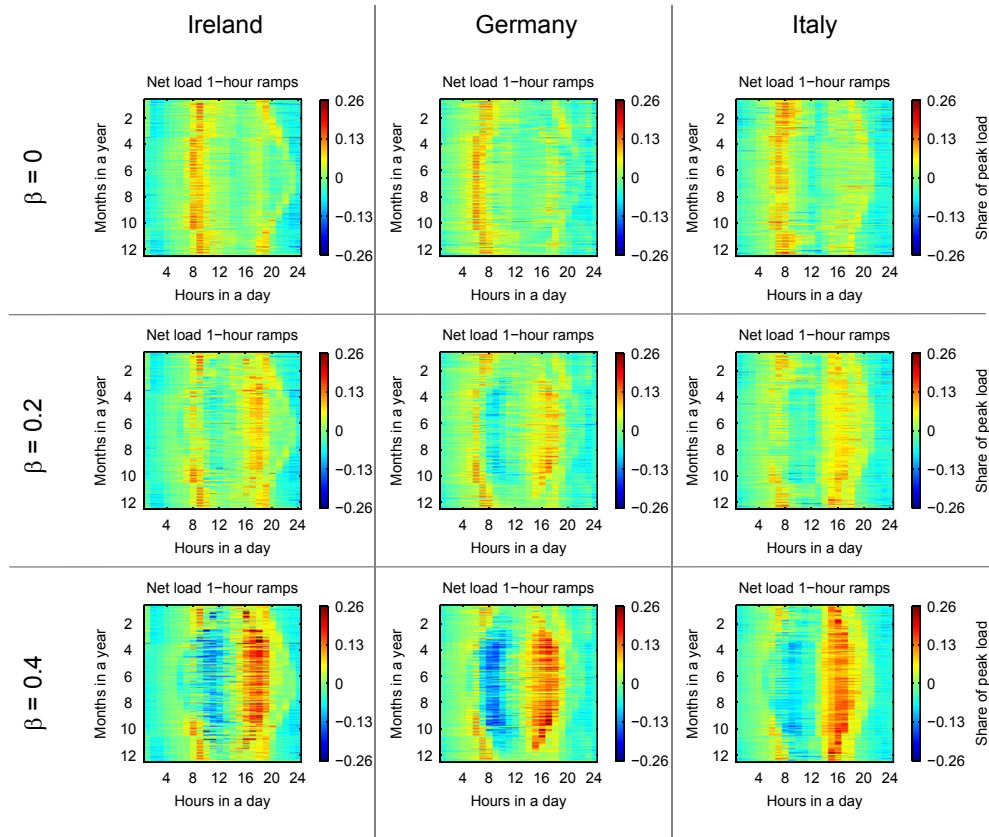
Fig. 6. Temporal distribution of 1-h net load ramps for different shares of PV in the wind/PV mix β at 50% penetration of variable renewables.

3.3. Multihour net load gradients

The unit commitment and dispatch process in power system operation requires considering more than just 1 h. Many of the conventional power plants included in this process have flexibilities that require a planning period of up to 24 hours. The startup times for coal power plants range up to 10 hours and for nuclear power plants even longer. Even CCGT power plants, which are often considered as a flexible option, require up to 4 hours for a cold start [13]. Therefore, the ramping capabilities of the power plant fleet in a system over multiple hours are crucial for system integration of variable renewables. Net load ramp requirements over different time horizons determine the optimal portfolio of conventional power plants and other flexible resources. Portfolios can differ tremendously; few fast power plants can in certain circumstances provide the same flexibility as many slow plants [13].

A method to display and analyze the ramp requirements over multiple hours are gradient envelopes as introduced e.g. in Ref. [12]. Fig. 7 depicts gradient envelopes for the 27 European countries at levels of renewable penetration $\alpha = \{0.1, 0.3, 0.5, 0.7\}$ and shares of PV power in the VG mix $\beta = \{0.2, 0.4, 0.6\}$. We show the 1st and the 99th percentiles of gradients, which are in our opinion crucial for future power system design: Extreme values will most probably not be predictable even shortly before occurrence and will thus be balanced by spinning reserves. This, however, is not the scope of our paper, but it seems reasonable that higher variability in net load will also lead to higher uncertainty and thus higher requirements for spinning reserves. Further research on the impacts of variability and uncertainty can be found for example in Ref. [30]. In addition, storage power plants that are only available part of the time can be used to handle extreme gradients that only occur in several hours a year. Extreme net load ramps in negative direction (sudden increase

of power generation from wind or PV) might also be handled by curtailing power directly at the ramp sources, the generators.

Several interesting observations can be described from Fig. 7 which have implications for power system planning:

- At low penetrations of $\alpha = 0.1$, the gradient envelopes of all countries and all β are close; differences are rare. The major gradients might still come from variation in load. 1-hour gradients are in the region of 10% of peak load. Even at a time horizon of 6 h, the ramps are all below 30% of peak load.
- Beginning with $\alpha = 0.3$, the ramps become significantly larger and mixes differentiate. Except for countries with very low wind FLH, the ramp envelope is shifted outwards with increasing β.
- An important trend that becomes evident with higher shares of VG ($\alpha = 0.5$ and $\alpha = 0.7$) is a clustering according to the three values of β. The differences arising from varying shares of PV power in the mix β tend to be larger than the differences between countries. At $\alpha = 0.5$, for each β-value the differences in the 1-hour gradients between countries show a standard deviation of only 2–3% of peak load, whereas the difference in the mean value of all countries, for example between $\beta = 0.4$ and $\beta = 0.6$, is 18–26%.

Tables 1 and 2 present the 1st and the 99th percentiles of the 1-hour and 6-hour net load gradients averaged across the 27 European countries for six different scenarios. The range and the standard deviations show the dispersion of values that the net load extremes can reach in different countries.

Next, we take two points on the envelope curves, the 1st and the 99th percentiles of the 6-h ramps, and show their location on the net load gradient duration curves in Fig. 8. On average, every second day a positive or a negative ramp occurs outside the 1st–99th
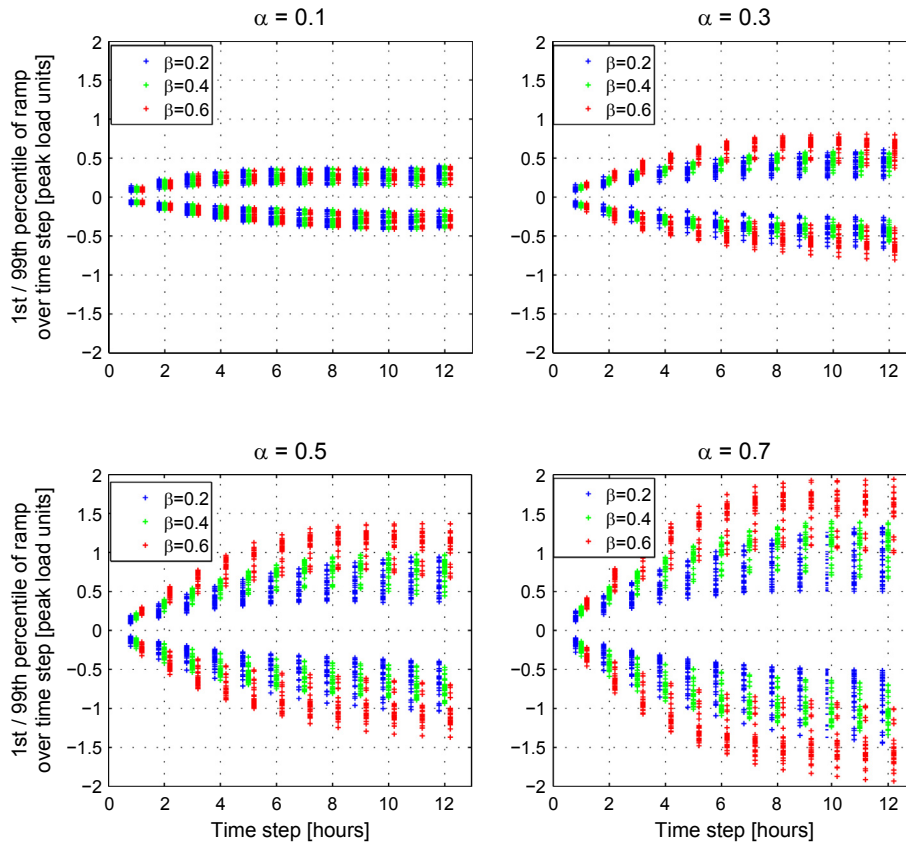
Fig. 7. Ramp envelopes for 27 European countries for different variable generation penetrations α and shares of PV in the wind/PV mix β, 2011.

percentile range whereas 2.4 ramping events per day occur on average outside the 5th–95th percentile range. Again, the differences between countries for one mix are smaller than the divergence caused by different mixes.

In a last analysis focusing on the influence of the wind/PV mix, we show the 99th percentiles for the 1-hour and 6-hour net load gradients, again for Ireland, Germany and Italy (Fig. 9). The first impression is that the images for the countries look similar supporting the finding that the mix is more important than the country analyzed. The maximum value is set to one for both time horizons. A net load ramp rate of one means that the whole conventional power plant park (including storage plants) has to ramp up in 1 or 6 hours. We see that 1-hour ramps are moderate (less than 25% of peak load) as long as α is below 0.3. From there on, the ramp rates start increasing dramatically, especially with β higher than 0.3. The behavior of Ireland and Germany is very similar whereas Italy shows lower gradients. For 6-hour ramps, a net load ramp of one is
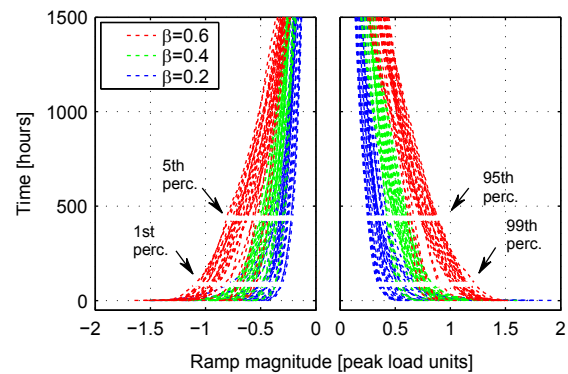

Fig. 8. Top and bottom 1500 hours of the 6-hour net load ramp duration curves for 27 European countries at 50% share of variable renewables and different shares of PV in the wind/PV mix β.

Table 1
1-hour net load ramp rates − mean of all countries and their statistical dispersion.

α	β	1-h ramps [share of peak load]	
		99th Percentile Mean (min/max/stdev)	1st Percentile Mean (min/max/stdev)
0.3	0.2	0.10 (0.07/0.16/0.02)	−0.08 (−0.13/−0.05/0.02)
	0.4	0.12 (0.09/0.15/0.02)	−0.10 (−0.14/−0.07/0.02)
	0.6	0.15 (0.12/0.19/0.02)	−0.13 (−0.19/−0.08/0.02)
0.5	0.2	0.13 (0.09/0.19/0.03)	−0.11 (−0.20/−0.08/0.03)
	0.4	0.18 (0.13/0.22/0.02)	−0.16 (−0.23/−0.10/0.03)
	0.6	0.26 (0.20/0.30/0.03)	−0.23 (−0.32/−0.15/0.04)

Table 2
6-h net load ramp rates − mean of all countries and their statistical dispersion.

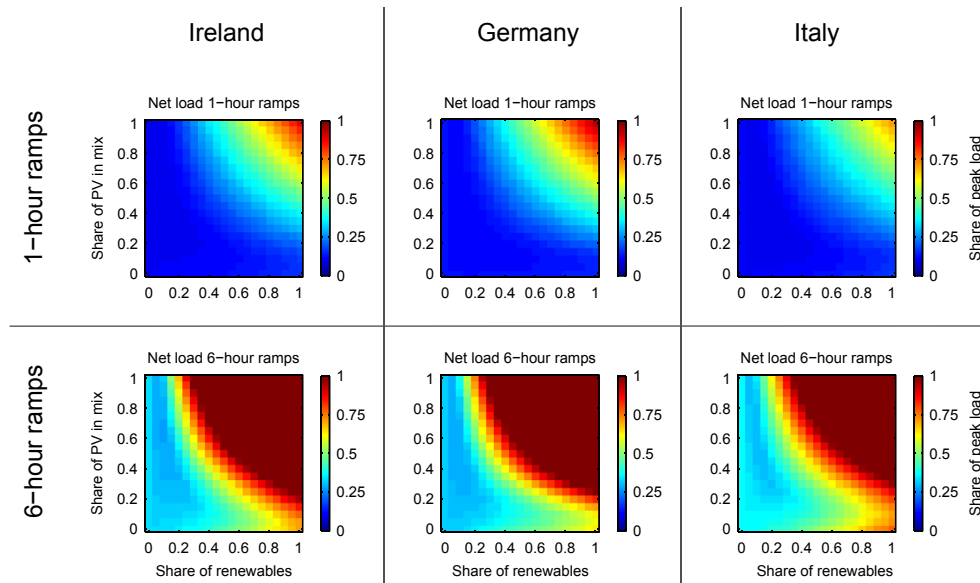| α	β	6-h ramps [share of peak load]	
		99th Percentile Mean (min/max/stdev)	1st Percentile Mean (min/max/stdev)
0.3	0.2	0.34 (0.23/0.48/0.07)	−0.34 (−0.52/−0.20/0.07)
	0.4	0.44 (0.33/0.50/0.05)	−0.36 (−0.44/−0.26/0.04)
	0.6	0.62 (0.45/0.72/0.07)	−0.50 (−0.62/−0.30/0.08)
0.5	0.2	0.50 (0.34/0.73/0.12)	−0.47 (−0.80/−0.30/0.13)
	0.4	0.72 (0.51/0.84/0.09)	−0.60 (−0.75/−0.37/0.11)
	0.6	1.04 (0.71/1.23/0.14)	−0.91 (−1.09/−0.55/0.15)

Fig. 9. 99th Percentiles of 1-hour and 6-hour net load ramps as a function of the variable generation penetration level α and the share of PV in the wind/PV mix β.

achieved with much lower α. Beginning with $\alpha = 0.3$ and high β above 0.5, the peak load has to be achieved within 6 hours. For PV shares β below 0.2, a much higher share of renewables can be integrated with lower 6-hour ramps.

The graphs in this section show the meteorological year 2011 but the development of the envelope curve is the same for the years 2001–2011. Even if the ramp rates were surprisingly similar in the analyzed countries, differences remain. An attempt to explain them is conducted in the next section.

4. Why are countries different – an attempt to explain diversity

We showed that the standard deviation of all countries for the 1st and 99th percentiles of 1-hour ramps is low with 2–3% of peak load (Table 1). Still, there are several countries where ramps have greater deviations from the European mean (up to three times the standard deviation). In this section, we aim to identify region-specific factors with strong influence on the flexibility requirements arising from variable generation. The factors we analyze are system size and the regional wind and PV ramp characteristics and full load hours determined by geographic location.

We focus on hourly net load gradients and look particularly at the highest and the 1st/99th percentiles of net load ramp occurrences because ramp behavior differs among countries the most in the extremes. Furthermore, hourly values are of particular interest for system operation and scenarios with higher hourly ramps were also shown to feature higher ramps over multiple hour time horizons (see Fig. 7).

Fig. 10 plots three interpercentile ranges of the net load ramp distribution for each country against the chosen region-specific factors: the minimum–maximum range, the 1st–99th and the 5th–95th percentile ranges. Scenarios are shown with shares of PV in the mix $\beta = \{0.2, 0.4, 0.6\}$ at combined VG penetration $\alpha = 0.5$. To account for the interannual variability of wind and solar power, net load time series are simulated using wind and PV data for each of the meteorological years 2001–2011. The percentiles of the net load ramp time series are then calculated for each year and finally averaged over all years. Those percentiles are plotted in Fig. 10 against the average wind and PV full load hours over the same period.

4.1. System size

The first row of Fig. 10 shows the relationship between country area and the magnitude of extreme hourly net load ramps. The smoothing effect of geographical dispersion on wind power fluctuations is well-known [14,31] and can be clearly observed in the wind power ramp rates in the model data we use. Although the ramp behavior of small regions is highly heterogeneous, large countries experience 1.5–2 times less extreme net load ramps than smaller ones in the mix with 80% share of wind ($\beta = 0.2$). Examining the effect of country area on the PV ramp time series shows that the magnitude of extreme ramps is only slightly reduced through larger system size and has almost no influence on the range between the 5th and 95th percentiles. That is why the smoothing effect of larger region area becomes less pronounced with a higher share of PV in the energy mix. With this analysis we found another important argument for increasing system size when wind power is deployed: not only reducing backup capacity requirements but also flexibility requirements in this potentially smaller backup system.

4.2. Wind and PV full load hours

The second influential factor to explain differences between countries is the resource availability in terms of FLH from wind and PV. The second row in Fig. 10 shows the influence from wind FLH, the third row from PV. We start with the influence of wind power: The lower the FLH, the higher the net load ramp extremes. This effect can be explained by the fact that the same share of wind energy in electricity consumption requires more installed capacity in a region with low FLH. The required capacity rises especially steeply in countries with wind FLH below 1500 per year. The effect of capacity dominates over the ramp structure of wind power production, whose impact is in the opposite direction: wind power ramps reach higher extremes in countries with high wind FLH than in those with low FLH. No systematic variation is observed between net load ramps and wind FLH with higher shares of PV in the system as PV ramps are not related to wind resource availability.

Regarding the influence of PV FLH, the third row of Fig. 10 shows that especially countries with medium FLH face high hourly net load ramp rates. This relationship holds both for systems with high
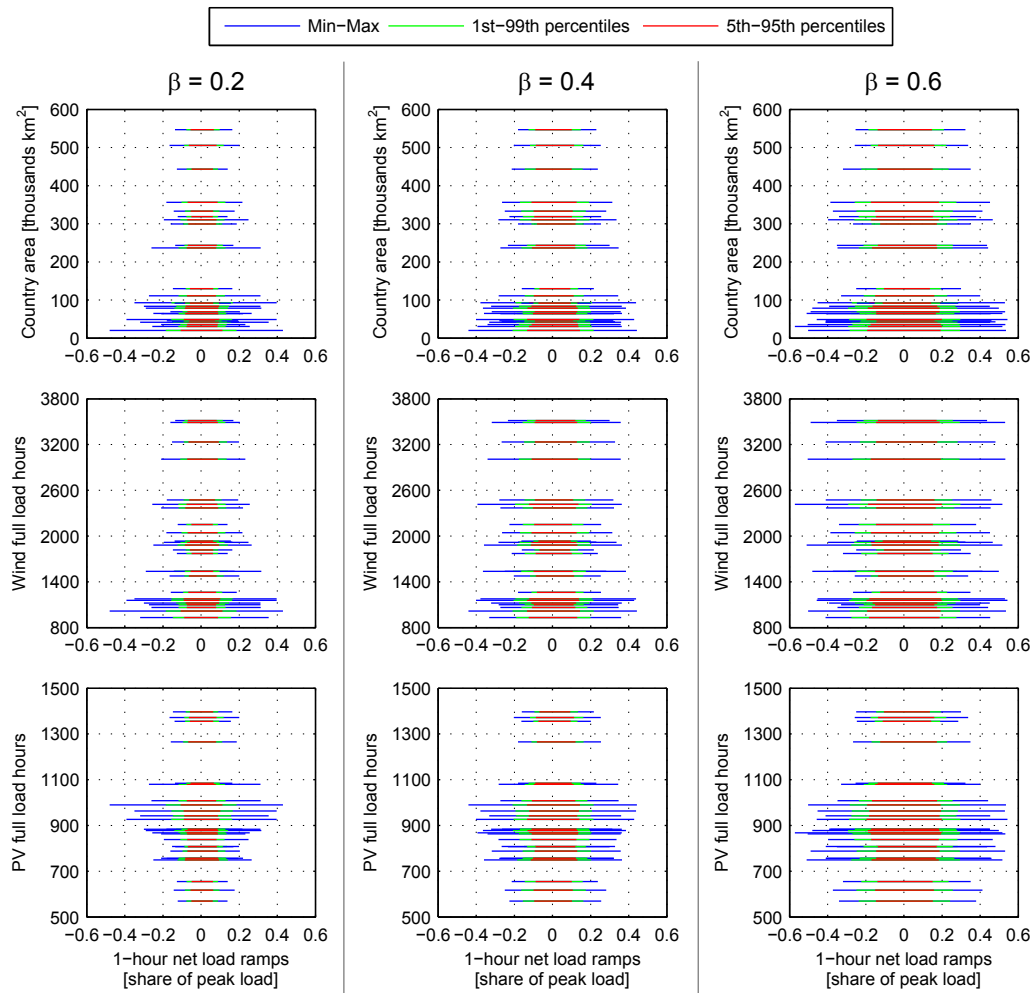
Fig. 10. Three interpercentile ranges of 1-h net load ramps for different shares of PV in the wind/PV mix β at 50% penetration of variable renewables.

wind and high PV shares in the mix and can be attributed to two effects in the same direction. First, it is partly not PV but wind power that causes the ramps: for all three interpercentile ranges the largest wind power ramps occur in countries with medium PV FLH between 900 and 1100 hours per year. This could be attributed to the stronger diurnal cycle of wind in Central Europe (along the North–South axis) as shown in Fig. 4. In some countries such as Hungary and Slovakia, this effect is amplified by low wind FLH, which increase the requirements for installed wind capacity. Second, the PV ramp extremes are also highest for countries with average PV FLH. In countries with higher PV FLH in the south of Europe, the impact of the lower PV capacities required dominates over the consistent increase in ramp extremes in the North–South direction. In Northern countries with low FLH the opposite is true — the effect of lower ramps inherent in the PV power structure outweighs the need for higher capacity.
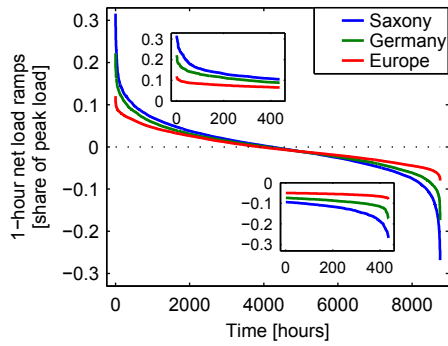
5. Benefits from cooperation

As shown in Fig. 10, larger geographical system size correlates with lower net load ramp extremes. In this section we quantify more precisely the reduction in flexibility requirements that can be achieved by interconnecting smaller regions into a large power system.
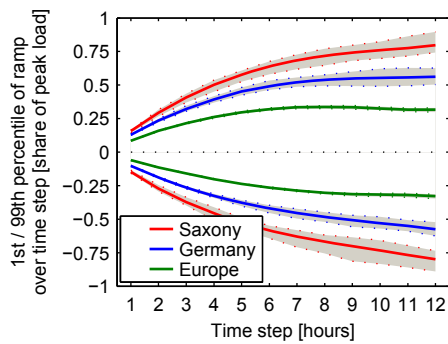
In order to illustrate potential effects, we compare the net load gradients in Saxony, Germany and Europe as a whole (see Section

2.2 for the derivation of the net load for Europe). Saxony was chosen as it has wind and PV characteristics similar to Germany. In Fig. 10 we showed that the gradient dependence on the region size is higher with larger shares of wind. It is mainly wind power extremes that can be reduced through leveling over regions. Thus, we choose the mix with $\beta = 0.2$ for the further analysis. Fig. 11 plots the hourly ramp duration curves at the three spatial scales. The effects from cooperation are tremendous, especially at the tails of the curves. At 50% wind and solar penetration, the maximum gradient is reduced from about 30% of peak load at the regional scale to 12% for interconnected Europe in the optimal case without transport restrictions. To what extent this ramp reduction potential will be exploited in the European system depends on reducing the grid restrictions between countries and the integration of their electricity markets.

Having seen the benefits of cooperation in the 1-hour time horizon, we extend our analysis to multihour ramps. In Fig. 12 we compare the ramp envelopes for Saxony, Germany and Europe again in the scenario with $\alpha = 0.5$ and $\beta = 0.2$. The 1st/99th percentile envelopes contain 98% of all gradients in each time horizon. Scenarios are simulated with each of the meteorological years 2001–2010, the percentile values are calculated for each of those scenarios and then averaged (shown by the solid lines). The range over this period is represented by the gray-shaded area. This plot shows clearly that gradients over all time steps are much lower if power systems are operated cooperatively. Furthermore, the

Fig. 11. 1-hour net load ramp duration curves at the regional, country and European spatial scales at 50% share of renewables and 20% PV in the wind/PV mix for the meteorological year 2009.

Fig. 12. 1st/99th Percentile ramp envelope at the regional, country and European spatial scales at 50% share of renewables and 20% PV in the wind/PV mix; average values for the period 2001–2010 and their range.

the most from a powerfully interconnected European power system. The maximum hourly change of net load in the European system is 11% of the peak load whereas small countries face hourly ramp extremes of 30–50% of peak load, e.g. in Switzerland and Slovenia. Even large countries like Germany can reduce the maximum ramp from 20% to 11%. Only very few countries like the Nordic countries would not benefit substantially; the ramp rates in Norway and Sweden are only slightly higher than in a European system.
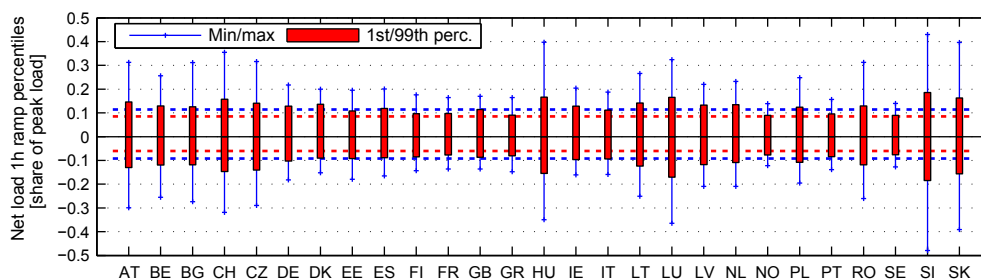
Our analysis provides additional arguments in support of large-scale transcontinental power systems with strong transmission grids, besides the benefits of reducing backup energy needs [33]. In Refs. [14,34], a power system spanning Europe and North Africa is shown to be cost-effective, mainly because of wind power smoothing. Several studies propose even a global super-grid to efficiently integrate renewable power sources [35,36]. Other authors focused on the very short term advantages of dispersing PV power generation [4]. Our results show advantages of cooperation in the timescale of 1–12 hours between the aforementioned very long-term horizon, concerned with capacity adequacy, and the short-term scales.

6. Conclusion and outlook

We have presented an analysis of time series of load, wind, PV and the resulting net load in scenarios for Europe that allow to quantify flexibility requirements in future power systems with high shares of variable generation. The analysis focused on deterministic flexibility needs at the temporal scale of 1–12 hours. This time frame is important for the unit commitment and dispatch process in power system operation.

We showed that increasing wind and solar power generation above a 30% share in annual electricity consumption will dramatically increase flexibility requirements. Especially, large PV contributions of more than 20–30% in the wind/PV mix will foster this trend. In scenarios about future net load, we found that the penetration level of wind and PV as well as their mix affect most European countries in our study in a similar way. Still, differences between countries exist which can to some extent be explained by country size as well as the annual wind and PV full load hours. In scenarios with high wind penetration, larger systems tend to face lower ramps. For example, we showed that at 50% variable generation penetration, the most extreme hourly net load ramp drops from 30% of peak load at the regional level to 22% for a large country and 11% for an interconnected Europe. Balancing larger, well-interconnected power systems can thus reduce ramp requirements substantially. This allows for advantages to be realized from cooperation among countries in Europe.

From this analysis we conclude that the future flexibility requirements in power systems in Europe will depend on three major parameters: the share of variable renewables, their mix and the balancing area size. Accommodating high shares of wind and solar

variation between years (gray-shaded area) becomes smaller with larger systems. This allows for less uncertainty in the system planning period. The effect is similar for the maximum ramps of each duration.

Requirements for the conventional power plants will decrease dramatically. These reductions in ramp rates will most probably lead to less start ups and wearing of the remaining thermal power plants, which can reduce costs and emissions [32]. A quantification of these effects is possible with the help of unit commitment models and will be done in further work.

Fig. 13 shows the reduction of extreme hourly net load ramp rates (the minimum/maximum and the 1st/99th percentiles) for the individual countries compared to the interconnected European system at 50% VG penetration. The values are again averaged over scenarios for the years 2001–2010. As discussed before, small countries have the highest ramp rates and will consequently benefit

Fig. 13. Boxplot with 1-hour net load ramp extremes for individual countries (solid lines/bars) and Europe (horizontal dashed lines) at 50% share of renewables and 20% PV in the wind/PV mix.

power will require that manufacturers develop more flexible components for power systems. System operators will have to fit their system to the upcoming renewable installations. Incentives for highly flexible power plants, storage as well as demand-side response will be beneficial for the system. From the results obtained we can also provide further arguments for aiming at transnational solutions as the most efficient way for large-scale integration of renewable power sources.

Putting the concept of flexibility into practice requires further research in several directions. A robust method has to be developed to match the flexibility needed in a system with the resources that can deliver it; this includes an appropriate market design. The effects of the uncertainty of variable generation and transmission network constraints also need to be integrated in the analysis. Moreover, the design of future power systems with high shares of variable renewables must ensure that flexibility requirements are met at all timescales. Besides the operational timescale of 1–12 hours that was the focus of our analysis, flexibility requirements in the time horizon of minutes are important for the design of automatic generation control schemes and those at timescales beyond 12 hours are relevant for developing a long-term storage system.

Acknowledgments

References

[1] Ma J, Silva V, Belhomme R, Kirschen D, Ochoa L. Evaluating and planning flexibility in sustainable power systems. IEEE Trans Sustain Energy 2013;4(1):200–9. http://dx.doi.org/10.1109/tste.2012.2212471.

[2] International Energy Agency. Harnessing variable renewables: a guide to the balancing challenge; 2011.

[3] Hedegaard K, Mathiesen BV, Lund H, Heiselberg P. Wind power integration using individual heat pumps – analysis of different heat storage options. Energy 2012;47:284–93. http://dx.doi.org/10.1016/j.energy.2012.09.030.

[4] Mills A, Wiser R. Implications of wide-area geographic diversity for short-term variability of solar power [Tech. rep.]. Ernest Orlando Lawrence Berkeley National Laboratory; 2010.

[5] Lannoye E, Flynn D, O'Malley M. Power system flexibility assessment – state of the art. In: IEEE power and energy society general meeting, San Diego, CA, USA, 22–26 July; 2012. http://dx.doi.org/10.1109/pesgm.2012.6345375.

[6] Mangesius H, Huber M, Hamacher T, Hirche S. A framework to quantify technical flexibility in power systems based on reliability certificates. In: 4th European innovative smart grid technologies conference, Lyngby, Denmark, October 6–9; 2013.

[7] Ulbig A, Andersson G. On operational flexibility in power systems. In: IEEE power and energy society general meeting, San Diego, CA, USA, 22–26 July; 2012. pp. 1–8. http://dx.doi.org/10.1109/pesgm.2012.6344676.

[8] NERC. Flexibility requirements and metrics for variable generation [Tech. rep.]. Princeton: NERC; August 2010.

[9] Holttinen H, Tuohy A, Milligan M, Lannoye E, Silva V, Müller S, et al. The flexibility workout: managing variable resources and assessing the need for power system modification. IEEE Power Energy Mag 2013;11(6):53–62. http://dx.doi.org/10.1109/mpe.2013.2278000.

[10] Lannoye E, Flynn D, O'Malley M. The role of power system flexibility in generation planning. In: IEEE power and energy society general meeting, Detroit, Michigan, USA, 24–28 July; 2011. pp. 1–6. http://dx.doi.org/10.1109/pes.2011.6039009.

[11] Holttinen H, Kiviluoma J, Estanqueiro A, Gómez-Lázaro E, Rawn B, Meibom P, et al. Variability of load and net load in case of large scale distributed wind power. In: 10th international workshop on large-scale integration of wind power into power systems as well as on transmission networks for offshore wind farms proceedings, Aarhus, Denmark, October 25–26; 2011.

[12] King J, Kirby B, Milligan M, Beuning S. Flexibility reserve reductions from an energy imbalance market with high levels of wind energy in the Western interconnection [Tech. rep. NREL/TP-5500-52330]. National Renewable Energy Laboratory; 2011.

[13] ETG-Task Force Flexibilisierung des Kraftwerksparks. Erneuerbare Energie braucht flexible Kraftwerke – Szenarien bis 2020 [Tech. rep.]. Frankfurt: Verband der Elektrotechnik, Elektronik und Informationstechnik e.V. (VDE); 2012.

[14] Czisch G. Szenarien zur zukünftigen Stromversorgung [Ph.D. thesis]. Universität Kassel; 2005.

[15] Heide D, Greiner M, von Bremen L, Hoffmann C, Speckmann M, Bofinger S. Seasonal optimal mix of wind and solar power in a future, highly renewable Europe. Renew Energy 2010;35(11):2483–9. http://dx.doi.org/10.1016/j.renene.2010.03.012.

[16] Schaber K, Steinke F, Mühlich P, Hamacher T. Parametric study of variable renewable energy integration in Europe: advantages and costs of transmission grid extensions. Energy Policy 2012;42:498–508. http://dx.doi.org/10.1016/j.enpol.2011.12.016.

[17] Rienecker Michele M, Suarez Max J, Gelaro Ronald, Todling Ricardo, Bacmeister Julio, Liu Emily, et al. MERRA: NASA's modern-era retrospective analysis for research and applications. J Clim 2011;24(14):3624–48. http://dx.doi.org/10.1175/jcli-d-11-00015.1.

[18] Janker K. Wind and PV power generation time series (unpublished). Chair for Energy Economy and Application Technology, Technische Universität München; 2013.

[19] German Transmission System Operators: Amprion, 50Hertz Transmission, TenneT and TransnetBW, Wind and pv power feed-in www.amprion.net, www.50hertz.com, www.tennettso.de, www.transnetbw.de [accessed 30.10.13].

[20] EirGrid plc. Wind generation. www.eirgrid.com [accessed 30.10.13].

[21] Dimkova D. System integration of variable renewable energy sources: flexibility requirements [Master's thesis]. Technische Universität München; 2013.

[22] ENTSO-E, European network of transmission system operators for electricity. Hourly consumption profiles. URL: https://www.entsoe.eu/data/data-portal/consumption/; 2011 [accessed 15.10.13].

[23] Heide D, Greiner M, von Bremen L, Hoffmann C. Reduced storage and balancing needs in a fully renewable European power system with excess wind and solar power generation. Renew Energy 2011;36(9):2515–23. http://dx.doi.org/10.1016/j.renene.2011.02.009.

[24] Steinke F, Wolfrum P, Hoffmann C. Grid vs. storage in a 100% renewable Europe. Renew Energy 2013;50:826–32. http://dx.doi.org/10.1016/j.renene.2012.07.044.

[25] Hewicker C, Hogan M, Morgren A. Power perspectives 2030: on the road to a decarbonised power sector. URL: http://www.roadmap2050.eu/attachments/files/PowerPerspectives2030_FullReport.pdf; 2011.

[26] Pryor S, Barthelmie R. Climate change impacts on wind energy: a review. Renew Sustain Energy Rev 2010;14(1):430–7. http://dx.doi.org/10.1016/j.rser.2009.07.028.

[27] Finn P, Fitzpatrick C. Demand side management of industrial electricity consumption: promoting the use of renewable energy through real-time pricing. Appl Energy 2014;113:11–21. http://dx.doi.org/10.1016/j.apenergy.2013.07.003.

[28] Dai A, Deser C. Diurnal and semidiurnal variations in global surface wind and divergence fields. J Geophys Res 1999;104(D24):31,109–31,125. http://dx.doi.org/10.1029/1999JD900927.

[29] Hodge B, Milligan M. Wind power forecasting error distributions over multiple timescales. In: IEEE power and energy society general meeting, Detroit, Michigan, USA, 24–28 July; 2011. pp. 1–8. http://dx.doi.org/10.1109/pes.2011.6039388.

[30] Ela E, O'Malley M. Studying the variability and uncertainty impacts of variable generation at multiple timescales. IEEE Trans Power Syst 2012;27(3):1324–33. http://dx.doi.org/10.1109/tpwrs.2012.2185816.

[31] Holttinen H. The impact of large scale wind power production on the Nordic electricity system [Ph.D. thesis]. Finland: VTT Technical Research Center; 2004.

[32] Keatley P, Shibli A, Hewitt N. Estimating power plant start costs in cyclic operation. Appl Energy 2013;111:550–7. http://dx.doi.org/10.1016/j.apenergy.2013.05.033.

[33] Becker S, Rodriguez R, Andresen G, Schramm S, Greiner M. Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply. Energy 2014;64:404–18. http://dx.doi.org/10.1016/j.energy.2013.10.010.

[34] Huber M, Dorfner J, Hamacher T. Electricity system optimization in the EUMENA region [Tech. rep.]. Dii GmbH; Jan 2012. URL:, http://mediatum.ub.tum.de/node?id=1171502.

[35] Chatzivasileiadis S, Ernst D, Andersson G. The global grid. Renew Energy 2013;57:372–83. http://dx.doi.org/10.1016/j.renene.2013.01.032.

[36] Aboumahboub T, Schaber K, Tzscheutschler P, Hamacher T. Optimal configuration of a renewable-based electricity supply sector. WSEAS Trans Power Syst 2010;5(2):120–9.