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# Wind Energy in Germany and Europe

Part 2*

## Status, potentials and challenges for baseload application: European Situation in 2017

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**Introduction** Wind power is a cornerstone of rebuilding the electricity supply system completely into a renewable system, in Germany referred to as "Energiewende" (i. e. energy transition). Wind power is scalable, but as intermittent renewable energy can only supply electrical power at any time reliably (security of supply) in conjunction with dispatchable backup systems. This fact has been shown in the first part of the VGB Wind Study, dealing with operating experience of wind turbines in Germany from 2010 to 2016 *[1],[2]*. This study states among other things that despite vigorous expansion of on- and offshore wind power to about 50,000 MW (92 % onshore, 8 % offshore) at year-end 2016 and contrary to the intuitive assumption that widespread distribution of about 28,000 wind turbines, hereinafter referred to as German wind fleet, should lead to balanced aggregate power output, no increase in annual minimum power output has been detected since 2010, each of which accounted for less than 1 % of the relevant nominal capacity.

### A question of grid losses

These observations illustrate that an increased interconnection in Europe would necessitate the transmission of electricity over very long distances. This raises the question of the extent of grid losses, as it has so far been the rule of thumb in the electricity industry to build power plants as close as possible to the consumer to keep grid losses low. These comprise load-dependent and load-independent losses, losses due to power transformation and losses from reactive power compensation. However, the majority of the losses are heat losses caused by the ohmic resistance of the power lines.

With the transmission of electricity via high-voltage alternating current (HVAC) overhead lines, specific total losses of around 1 % per 100 km transport distance arise *[26]*, which remain roughly constant across a broad range of transmission capacities.

Current technical limits in terms of HVAC transmission are extra high voltage of around 765 kV, transmission capacities of up to 3,000 MW and transport distances up to around 1,000 km, the latter being limited by transmission angle and reactive power requirement *[27]*.

With established high-voltage direct current (HVDC) transmission via overhead lines with ±500 kV, specific grid losses of around 0.5 % per 100 km have to be factored in *[26]*. Converter stations are required here at both end points of the transmission route to transform alternating current into direct current and vice versa, and each of these causes additional losses of around 1 % of the transmission capacity *[26],[27]*.

At present, HVDC transmission routes via overhead lines are designed for extra high voltages of ±800 kV, transmission capacities of around 6,400 MW and transport distances of up to about 2,000 km. With extra high voltages of this kind, the specific conduction losses fall to just under 0.4 % per 100 km transport distance. Technical limits in terms of HVDC transmission are extra high voltages of ±1,100 kV, transmission capacities up to 12,000 MW and distances up to 3,300 km *[28]*.

For HVAC transmission via 380kV overhead lines over an average transport distance of 1,500 km between centers of national wind fleets in 18 European countries, grid losses of at least 15 % of the transmission capacity would have to be expected, if considered seriously at all. In the case of HVDC transmission with ±500 kV the level would be just under 10 % *[26], [27]*.

For long-distance transport of electricity over the longest single distances considered here between wind fleet centers of peripheral countries like Finland or Norway (Scandinavia), Portugal or Spain (Iberian Peninsula) and Greece (Aegean) and Romania (Balkan Peninsula) of around 3,000 km or more, HVAC transmission would probably not be considered, as high grid losses of 40 % or more of the transmission capacity would have to be factored in *[26]*. In case of HVDC transmission, too, grid losses amounting to one fifth of the transmission capacity would have to be expected with transport distances of this order *[26]*.

In all cases cited above, further grid losses would have to be added for collecting and stepping up the power output of the wind turbines in the producing country to a suitable voltage level and the further distribution of the transmission capacity remaining after the long-distance transport to the end consumer in the country of destination via extra high, high, medium and low voltage networks.

These grid losses can be quantified with data from the Council of European Energy Regulators (CEER) and the US Energy Information Authority (EIA) for the years 2010 to 2015 (**Table 2**) *[29],[30]*.

In total, and averaged over several years and all 18 countries, grid losses of around 6.6 % of the annual electric energy fed into the grid have to be factored in for an average European country for the transport and distribution of electricity from the power plant to the end consumer. These losses are split across the voltage levels extra high, high, medium and low *[7]*.

In Germany, voltage in the extra high voltage network is 380 or 220 kV. At present, the extra high voltage network is responsible for large-scale, nationwide connections and supplies to regional electricity suppliers and large industrial companies. It is almost 37,000 km long and is linked via interconnectors with the European grid.

The high voltage network is operated at a voltage of 110 kV and about 97,000 km long. This regional distribution network particularly transfers electricity to industrial companies, local electricity suppliers or transformer substations. Voltage is stepped down to medium voltage level here, mostly 20 kV, for supplying to industrial companies and businesses. The circuit length of this network is about 520,000 km.

Private households, businesses and the agricultural sector only have electrical devices designed for voltages of 230 V or 400 V. In order to be fed into the local low voltage network, medium voltage has to be converted again. With its circuit length of around 1,190,000 km, the low voltage network is the longest supply network.

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| Country | Mean grid losses in % of total annual electric energy fed into the grid | | | | | |
|---|---|---|---|---|---|---|
| | Transport and distribution1) | | | Transport only2) | | |
| | Ø3) | 2010 | 2015 | Ø3) | 2010 | 2015 |
| AT | 4.8 | 4.7 | 4.9 | 0.9 | 0.8 | 0.9 |
| BE | 4.9 | 4.7 | 4.7 | 1.7 | 1.6 | 1.7 |
| CZ | 5.0 | 5.5 | 5.6 | 1.0 | 0.8 | 1.1 |
| DE | 4.1 | 4.0 | 4.6 | 1.0 | 0.7 | 1.4 |
| DK | 6.0 | 6.0 | 5.6 | 2.2 | 2.0 | 2.3 |
| ES | 9.5 | 9.4 | 10.5 | 1.4 | 1.6 | 1.5 |
| FI | 3.3 | 2.8 | 2.6 | 0.8 | 0.8 | 0.8 |
| FR | 6.5 | 6.7 | 7.3 | 2.1 | 2.2 | 2.1 |
| GR | 7.0 | 7.1 | 9.7 | 2.5 | 2.8 | 2.5 |
| IE | 8.0 | 8.1 | 8.1 | 2.0 | 2.0 | 2.0 |
| IT | 6.9 | 6.7 | 6.4 | n.a. | n.a. | n.a. |
| NL | 4.8 | 5.0 | 4.6 | 0.9 | 1.1 | 1.0 |
| NO | 6.3 | 7.6 | 6.2 | 1.7 | 1.9 | 1.5 |
| PL | 7.0 | 8.2 | 6.9 | 1.2 | 1.2 | 1.2 |
| PT | 9.6 | 8.5 | 10.1 | 1.4 | 1.5 | 1.3 |
| RO | 11.9 | 12.6 | 12.5 | 1.6 | 1.8 | 1.5 |
| SE | 5.0 | 4.9 | 3.8 | 0.9 | 1.0 | 0.9 |
| UK | 7.8 | 7.2 | 8.5 | 1.8 | 1.5 | 2.1 |
| **Ø4)** | **6.6** | **6.7** | **6.6** | **1.5** | **1.4** | **1.4** |

**Tab. 2.**
Mean grid losses for transport and distribution in the 18 European countries in percent of total annual electric energy fed into the grid from 2010 to 2015.
1) including extra high, high, medium and low voltage 2) extra high voltage only 3) Averaging for the years 2010 to 2015 and the sources CEER *[29]* and EIA *[30]* 4) Averaging for the 18 European countries

**Table 1** illustrates that by far the lowest transport and distribution network losses across all voltage levels are to be found in Finland with around 3.3 % of the electric energy fed in annually, followed by Germany (4.1 %), then Austria (4.8 %) and the Netherlands (4.8 %).

The highest value is to be found in Romania, at 11.9 %, followed by Portugal (9.6 %) and Spain (9.5 %). In relation to electricity consumption, the grid losses averaged over several years and all 18 countries amount to around 7.3 %.

In absolute figures, the losses from the transport and distribution networks of 18 countries in relation to the total annual electric energy fed into the grid to provide all end consumers in these countries at present add up to around 200 TWh per year *[30]*. This is around double last year's generation of electricity from solar power of these countries, or about 60 % of their electricity generation from wind power *[15]*.

Averaged over several years and all 18 countries, grid losses of about 1.5 % of the annual electric energy fed in arise for an average European country when electricity is transported at extra high voltage level. Here, too, country-specific differences can be observed. Finland, for example, has the lowest losses, with 0.8 % of the annual power fed in, followed by Austria (0.9 %), Sweden (0.9 %) and the Netherlands (0.9 %).

In the case of Germany (1.0 %), it has to be added that the losses in the extra high voltage network doubled from around 0.7 % in 2010 to 1.4 % in 2015. With specific total losses at extra high voltage level of around 1 % per 100 km transport distance, the losses in the extra high voltage network can also be interpreted as doubling of the average power plant distance from the end consumer from around 70 to 140 km in the past six years. The share of losses of the extra high and high voltage networks in the total grid losses has increased in Germany at the same time from 33 to 43 % *[7]*.

In many European countries, the share of decentralised power generation plants in the nationwide power plant capacity has significantly increased over the past years. These plants normally feed into the medium and low voltage networks, and in some cases also into the high voltage networks. Grid losses should tend to fall when decentralised power plants move closer to the end consumer, as not only does the distance for transporting and distributing electric power output decrease, but so too does the need for transforming.

However, this does not apply without restriction, as the local synchronicity of generation and consumption likewise influences the grid losses: if decentrally supplied electricity can be used at the same time directly by the local consumers, the grid losses diminish very significantly, as transport to consumers further afield is not necessary.

In reality, however, weather-dependent power output from renewable energies frequently lead to situations in which decentrally generated electricity cannot be used locally at the same time, resulting in backflows in the network which increase the grid losses. Wind farms, too, are often not in the direct vicinity of centres of consumption. Their power output has to be fed into extra high and high voltage networks and in some cases transported over long distances, as a result of which grid losses increase. Here, too, the influence of the synchronicity of generation and consumption is not negligible.

The example of the Spanish distribution system operator Viesgo *[29]* illustrates how grid losses can increase significantly with a high share of decentralised power generation. This operator found that electricity generation from wind power in his distribution network led to grid losses significantly increasing at high voltage level (132 kV). Depending on the power flows in his grid area or power outputs transferred between two grid nodes, the distribution system operator registered an increase in grid losses generally in the region of 2 to 4 % of the total of load and export-import balance to higher and extreme values of up to 20 % in cases where net electricity imports into his grid area were necessary.

These findings illustrate that grid losses in connection with further expansion of electricity generation from wind power with interconnection throughout Europe cannot be considered negligible, especially against the backdrop of European efforts to increase efficiency.

In a scenario according to the motto "everyone helps everyone else", it is true to state for the grid losses with enhanced interconnection across Europe that in the producing nation, the power output from all wind turbines would, in a first step, have to be collected and transformed to the appropriate voltage level before, in a second step, the long-distance transport either to the domestic consumer or to the country of destination over an average distance of 1,500 km could take place. In a third step, the power output would then have to be transformed there to a lower voltage level and finally distributed further to the end consumer. As a simplified engineering estimate, the grid losses over all three stages in this scenario could add up to around one fifth to one third of the aggregate output fed into the grid (producing nation: ≈ 7 %, long-distance transport: ≈ 10 to 15 %, country of destination: ≈ 7 %).

On the question of the secured capacity of wind power available throughout Europe, this means that, in reality, lower values should result from the total power output of all wind turbines in 18 European countries with greatly idealising disregard of the transport and distribution network losses.

## Discussion

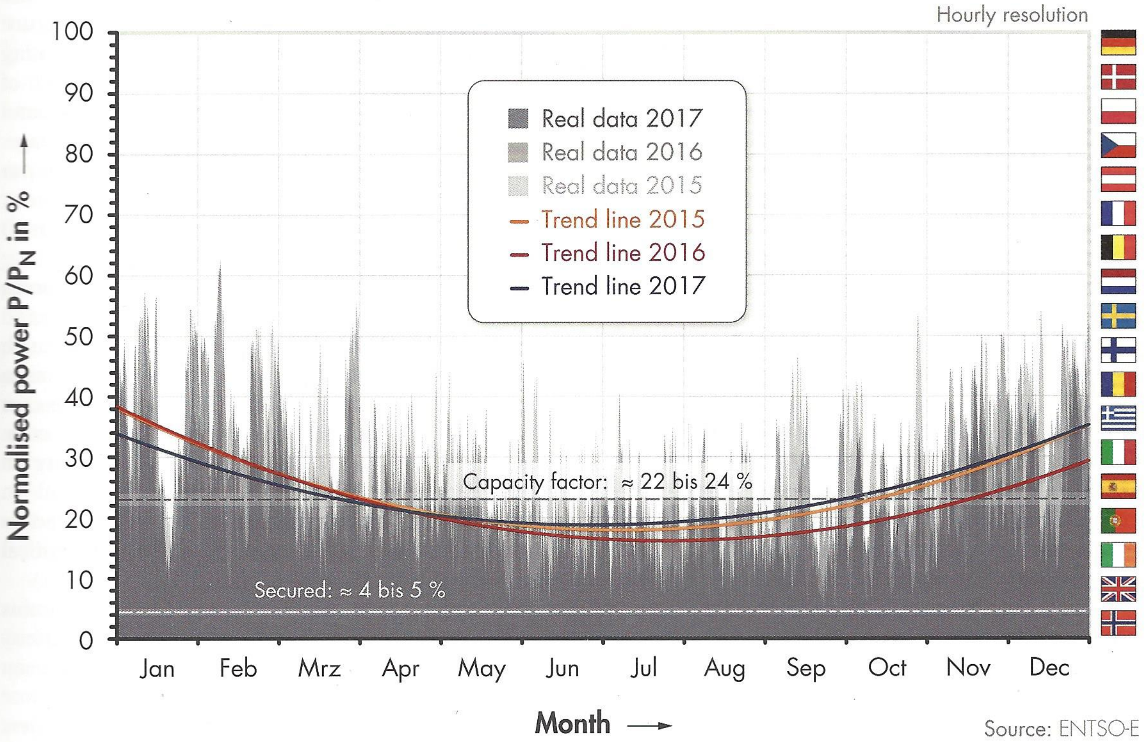
Analyses of cumulative power time series of the European wind fleet in the high-wind years 2015 and 2017 suggest a secured capacity of around 5 % of the nominal capacity in each case for the European wind fleet, on the assumption of linear expansion during the course of the year. The less windy year 2016 led to a secured capacity of the European wind fleet of 4 % of the nominal capacity **(Figure 12)**.

During the period 2015 to 2017 the power output of the European wind fleet ranges from 4 to 63 % of the nominal capacity and is highly volatile. The trend lines for the power time series of the European wind fleet of these three years are included for clarity, and illustrate that changes are essentially determined by the annual availability of wind. The seasonal pattern of electricity generation from wind power familiar in Germany – higher aggregate output in the winter than in the summer – also applies with distribution of wind turbines throughout Europe.

Effects on the annual power output minimum of an expansion-induced increase in the distribution of wind turbines throughout Europe are not apparent, although the nominal capacity of 141,000 MW at the start of 2015 increased by one third to just under 170,000 MW at year-end 2017.

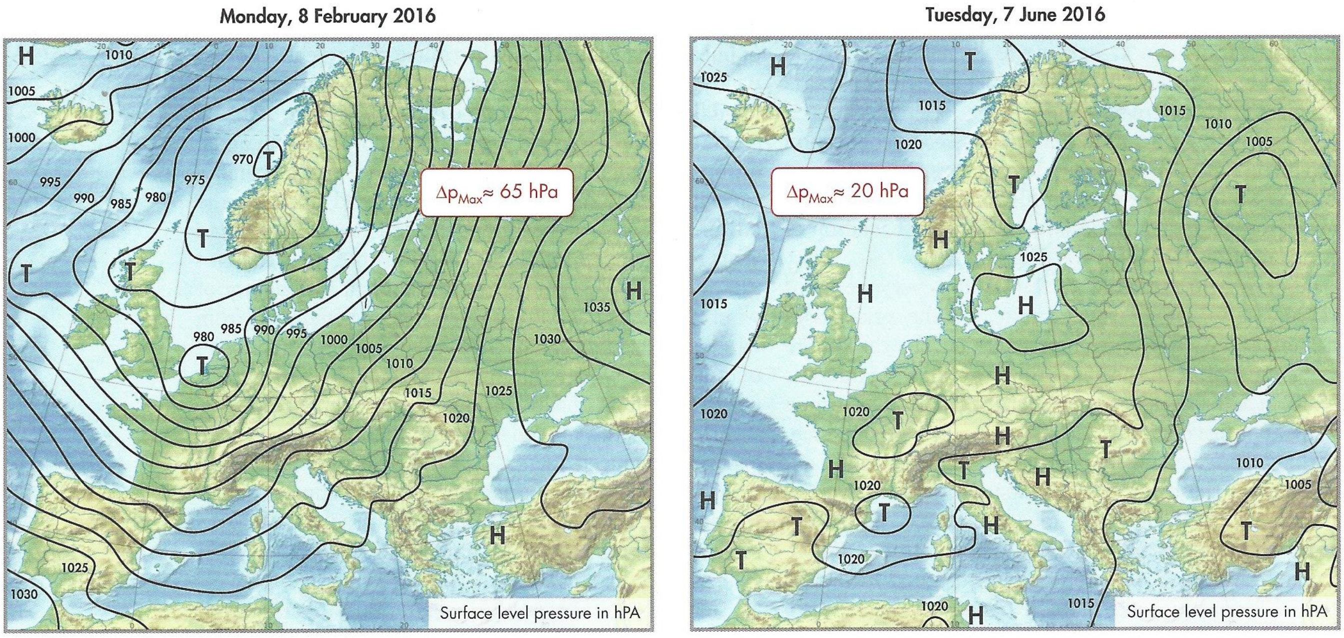
This means that even if, from a European perspective, statistically significant smoothing effects are to be seen, these effects clearly only help to achieve secured capacities to a limited extent, since 4 to 5 % of the nominal capacity with consideration of the grid losses means that, even at European level, dispatchable backup capacity of practically 100 % of the nominal capacity of the European wind fleet has to be maintained, as long as its nominal capacity has not yet exceeded the cumulative annual peak load of all countries concerned plus reserves.

In 2017 the European wind fleet supplied a total 339 TWh of electricity, in 2016 and 2015 just under 287 TWh and 285 TWh respectively. The capacity factor of the European wind fleet varied between 22 and 24 %. The results of the linear regression analysis described previously enable the capacity factor of a wind fleet in an individual European country to be determined with good



Source: ENTSO-E

**Fig. 12.**
Cumulative time series of normalised power output of the European wind fleet for the years 2015 to 2017 with three trend lines illustrating the seasonal character of electricity generation from wind power, on the assumption of a linear increase in nominal capacity during the course of the year. The secured capacity of the European wind fleet is 4 to 5 % of its nominal capacity and the capacity factor 22 to 24 %.



Monday, 8 February 2016

Tuesday, 7 June 2016

**Fig. 13.**
Isobar maps of 8 February 2016 (winter day) and 7 June 2016 (summer day) as examples of pronounced high-wind and low-wind phases across much of Europe.

approximation to an average of 18 %. European interconnection therefore indicates a capacity factor benefit of a few percentage points of the nominal capacity.

In July 2017, researchers from ETH Zurich and Imperial College London concluded, on the basis of European weather data from the past 30 years and iRES model calculations *[23]*, that weather regimes with spatial scales of around 1,000 km and temporal scales of more than five days regularly occur in Europe resulting in an extensive lack of power output of wind fleets of neighbouring European countries.

Grams et al. recommended that expansion of wind power in Europe be better coordinated and account be taken of the fact that in peripheral European regions like the Iberian Peninsula, northern Scandinavia, the Balkan region or the Aegean, opposite wind conditions frequently prevail with which variations in the aggregate power output can be compensated at an overall European level. Expansion of wind power should thus focus more on peripheral European countries in order to balance electricity generation from wind power. Were the European nations to coordinate their expansion strategy even more closely, they could stabilise the generation of electricity from wind power, and it would then also be easier to integrate it into the energy system.

Grams et al. state that photovoltaics could also be used at a local level (during the daytime) to achieve pan-European balance. However, the currently available nominal capacity of around 114,000 MW at year-end 2017 in Europe *[15]* would have to be increased at least ten-fold.

As weather reports on television have shown, extensive weather regions can regularly occur throughout the whole of Europe with distinct phases in which strong wind or weak wind prevails across many European countries at the same time. The driving force behind the wind are large-scale differences in air pressure, from which conclusions can be drawn about continental wind conditions on the basis of isobar maps (lines at constant pressure), as illustrated in **Figure 13** with the example of a winter day (8 February 2016) with good wind over much of Europe and a summer day (7 June 2016) with weak wind over much of Europe.

On 8 February 2016, maximum differences in air pressure $\Delta p_{Max}$ up to around 65 hPA occurred across Europe. The isobar lines for this winter day run closely staggered next to each other. This indicates high gradients and good wind conditions. Wind turbines in the 18 European countries considered here as European wind fleet supplied around 86,000 MW or 57 % of their nominal capacity of around 152,000 MW on daily average (prerequisite: copper plate across Europe, no grid losses). Between 20:00 and 21:00 in the evening, the power output of the European wind fleet reached its annual peak (hourly resolution) at 89,100 MW *[13]*.

On 7 June 2016, maximum differences in air pressure $\Delta p_{Max}$ of around 20 hPA occurred across Europe. In **Figure 13**, comparatively few isobars are apparent, indicating low gradients and weak wind conditions across much of Europe. The European wind fleet supplied around 12,200 MW or 8 % of its nominal capacity on daily average. Between 06:00 and 09:00 in the morning, its power output fell to around 6,500 MW or 4 % of its nominal capacity (prerequisite: copper plate across Europe, no grid losses) *[13]*.

These examples illustrate that situations can occur again and again in which electricity generation from wind power is simultaneously strong or weak throughout much of Europe. In such cases this means: if wind conditions in Germany are favourable, then this is also often the case in neighbouring countries and vice versa. This is compounded by the fact that demand for electricity in European countries is also temporally correlated in many cases, so that a cross-border balancing effect is demonstrably not a given certainty at the most critical point in the year for the load *[31]*.

According to the analyses carried out by Grams et al. *[23]*, synchronicity and correlation of electricity generation from wind power in neighbouring European countries could be avoided by connecting up very remote countries at the peripheries of continental Europe. In view of an increased need for transport of electricity over very long distances of several thousand kilometres and average iRES capacity factors of currently typically around 21 % for onshore wind power, 32 % for offshore wind power and

11 % for photovoltaics, this would raise justified questions as to the grid losses to be expected with expansion strategies of this kind, the capacity factor of the new infrastructure required with a focus on intensified pan-European long-distance transport of electricity and as to their profitability. The average capacity factors given above are calculated from hourly ENTSO-E power output data of 18 European countries from 2015 to 2017 accounting for 95 % of Europe's wind power and photovoltaic nominal capacity.

Even if China, for example, today has numerous HVDC routes for transport distances of one to two thousand kilometres, these are all designed to transmit electric power of several gigawatts from the large inland hydropower plants to supply the consumption centres on the country's coasts with electricity. This electricity transmission technology is also referred to as bulk transmission of electric power, an indicator of continuous power transmission and consistently high capacity factors of such transmission routes – criteria which neither wind nor solar power has any prospect of fulfilling at a European level.

At the beginning of March 2018, the German National Meteorological Service (DWD) published results of a study *[24]* showing that through the combined use of wind power and photovoltaics in the European power grid, risks due to wind lulls and phases with little sun could be significantly reduced. With measurement data on the spatial and temporal structure of the weather conditions from 1995 to 2015 and models to estimate electricity generation of representative wind power and photovoltaic systems, uniformly distributed across Europe without restrictions and disregarding any grid losses, the meteorologists determined how often the aggregate output of this iRES plant fleet would have been less than 10 % of the nominal capacity over a continuous period of two days in each case.

The result for Germany: with restriction to onshore wind power, 23 cases per year would be probable. If offshore wind power in the German North and Baltic Seas is added, this number is reduced to 13 cases per year, while further addition of photovoltaic systems brings a reduction to two cases per year and, if Europe is considered as a whole, the result is just 0.2 cases per year. However, as the weather pleases itself, it can never be ruled out that an extreme lull could occur in conjunction with a phase of little sun across Europe. Responsible energy policy must therefore not only be about expanding wind power and photovoltaic systems, but also ensuring sufficient reserve power plant capacities.

In view of the grid being required to maintain a permanent balance between electricity generation and consumption, it is necessary here to point out that, contrary to taking into account two-day periods in the cited study, already a fraction of a second or minutes can be sufficient to cause a blackout.

What would the consequences be, were wind turbines to be distributed in balanced form across Europe as recommended by Grams et al. *[23]* and Becker *[24]*?

As **Figure 3** illustrates, many countries have a considerable amount of catching up to do in relation to Germany: all 13 countries in the nominal capacity of their winds fleets ranking after Italy, for instance, would have to increase their wind fleet's nominal capacity sixteen-fold on average with as balanced distribution of locations as possible, in order to reach Germany's level of development.

When all 17 countries are considered, a total new nominal capacity of around 840,000 MW would have to be established. With the already existing nominal capacity of wind turbines in these 18 countries, a nominal capacity of the balanced European wind fleet of around 1,000,000 MW in total could therefore be expected.

By comparison: in 1995, power plants with a nominal capacity of around 620,000 MW were in operation in the 18 European countries considered here *[32]*. This had already risen to around 970,000 MW nominal capacity in 2015, 47 % of which was accounted for by conventional power plants, followed by hydropower plants (16 %), wind turbines (14 %), nuclear power plants (12 %) and photovoltaic systems (10 %).

With a long-term annual yield of the European wind fleet averaged across the 18 countries of around 2,000 MWh electricity per megawatt of nominal capacity *[15]* and on the assumption that yield-boosting factors such as ever larger plants and hub heights as well as yield-reducing factors like ever lower potential wind yields of remaining wind turbine locations roughly maintain a balance in the course of further expansion, the annual generation of around 2,000 TWh of electricity could be assumed for the imaginary European wind fleet. In comparison, the gross power generation of the 18 European countries considered amounted to just under 3,300 TWh in 2017 *[15]*.

With specific investment costs of 1.5 million euros per megawatt onshore nominal capacity *[33]* and 4.0 million euros per megawatt offshore nominal capacity *[34]*, total investments of about 1,500 billion euros would have to be factored in for expansion of the European generation of electricity from wind power of this order, on the assumption that 90 % of the nominal capacity to be added would still be accounted for by onshore wind turbines and the rest by offshore wind turbines. Compared with the gross domestic product of the 18 countries in 2015 of almost 11,500 billion euros, this is a considerable sum.

At the same time, further investments worth billions would have to be factored in for still necessary dispatchable backup systems and in order to enhance the network infrastructure *[35]*, *[36]*. According to ENTSO-E estimates, around four fifths of grid congestion problems identified throughout Europe are attributable to renewable energies. ENTSO-E puts the costs for enhancing and strengthening the European grid for further integration of renewable energies at just under 130 billion euros *[36]*.

Another aspect to be considered: Assuming that today's wind turbines have an operational lifespan of an average 25 years, a renewal rate of 40,000 MW per year would be required with a plant level of around 1,000,000 MW nominal capacity. By comparison, wind turbines with an average nominal capacity of 12,000 MW per year went into operation in the 18 countries in the last six years, while in 2017 the figure was slightly over 15,000 MW *[15]*.

Evaluations of long-term operating data from the United Kingdom and Denmark for 2002 to 2012, the results of which indicate the influence of material ageing and an economic operational lifespan more in the region of twelve to fifteen years, demonstrate that the operational lifetime of wind turbines can, in reality, be considerably lower *[37]*.

This was confirmed, for example, in March 2018 *[38]*: the Danish energy company Ørsted identified unexpected damage to around 2,000 wind turbines in Danish and British waters which had only been in operation since 2013. The leading edges and tips of the rotor blades were so severely damaged by the impact of salt particles and rain that they had to be replaced.

Further confirmation followed in April 2018 *[39]*: in the offshore wind park Alpha Ventus around 45 kilometres off Borkum, half a nacelle of a wind turbine, together with the plastic casing, plunged into the depths from a height of around 90 meters. At the time the damage occurred, the turbine was around eight years old. The wind farm operator reported a broken retaining bolt of the nacelle carrier as being the cause. No information was given as to whether this was an isolated incident or a case of serial damage. As a precautionary measure, the remaining five undamaged Alpha Ventus turbines have since run in idle mode and been closed for maintenance.

Even if damage to offshore wind turbines, as a comparatively new technology, is not unusual, the German television channel NDR interpreted this incident as being major damage possibly in connection with material fatigue, and called for speedy clarification of the cause of the damage, since more than 120 turbines of this type are currently in operation in the North Sea.

Wind turbines do not only transport the wind intermittency, i.e. briefly occurring strong gusts of wind into the power grid, they also even intensify it when converting it into electrical output *[40],[41],[42],[43]*.

Measurement data with high temporal resolution substantiate strong fluctuations in wind speed and changes in power output of a 2 MW wind turbine by 80 % of its nominal capacity in eight seconds, and of a wind farm comprising twelve 2 MW wind turbines by 50 % of its nominal capacity in two minutes at a northern German onshore location *[40]*. Within a quarter of an hour, therefore, wind turbines can pass through power outputs from almost zero up to the nominal capacity according to their power curve.

The working conditions of wind turbines are characterised by intermittent, turbulent air flows which are reflected in turbulent power output fluctuations of both individual wind turbines and larger turbine fleets *[41]*.

Peinke et al. *[40]* report that with individual wind turbines and large wind farms alike, extreme fluctuations which would only be to be expected every three million years with normal distribution could occur once a month on statistical average. This property is particularly relevant for grid stability analyses and the design of wind turbines, as these face immense changes of load – comparable with those of an aeroplane in an imaginary landing approach lasting several years with severe wind turbulence.

This is caused by turbulences impacting the turbines within a matter of seconds, the footprint of which is also reflected in the electric power output. Grid instabilities caused by power fluctuations of this kind would likely increase with the expansion of wind power – as too would the regulatory effort involved in compensating them *[41]*.

Redispatching measures on the part of transmission system operators are an indicator of grid instabilities and resulting regulatory network intervention. This is to be understood as intervention in the market-based original power plant schedule in order to relocate power feed-in so as to prevent or eliminate overloading in the power grid.

During the period 2010 to 2015, the annual redispatched power output from domestic measures increased by more than 36 times to 11.2 TWh, then fell by one third in 2016 to 7.5 TWh before climbing to another new peak of 11.3 TWh in 2017 *[44]*. The annual redispatched power output generated by the power plants in neighbouring countries and in the context of cross-border trade as of 2014 amounting to around 25 to 50 % of the corresponding domestic annual power output has to be added to this.

The development over the past years invites comparison with the electricity generation from wind power: 2015 and 2017 were very windy years, while 2016 was considerably less windy. Overall, the development of the mean value $P_\mu$ from 2010 to 2017 as shown in **Figure 1** as a measure of the annual electricity supplied is similar to the development of the annual redispatched power output, which could indicate causal relationships *[44]*.

On account of massively increasing interventions in grid operation, the German Federal Network Agency introduced quarterly reports on grid and system security measures as of 2015 *[45]*, pointing out that in view of the drastic increase in grid and security interventions, annual recording was no longer sufficient, and that measures for securing grid stability had become more important, as the transmission system operators were facing ever greater challenges in view of the changing power generation landscape. This change, it was stated, was characterised above all by the expansion and regional distribution of wind turbines with impacts on the conventional power plant fleet. Weather effects like low-pressure systems or long sunny periods additionally led to high peaks in power output from wind power and photovoltaics – a development which also becomes clear from a glimpse into the control rooms of the transmission system operators: whereas grid control engineers had to actively intervene twice in the whole of 2003 to adjust the grid operation, three to four interventions per day have now become the norm.

Apart from the fact that with each intervention the probability of human error by nature increases, this development also indicates that exceptional circumstances in the power grid necessitating intervention have drastically increased since 2003.

Statements made in June 2017 by Dr. Klaus Kleinekorte, Technical Managing Director at Amprion GmbH in Dortmund, verify the occurrence of at times extreme loads in the transmission grid *[46]*. He stated that between December 2016 and February 2017 there were repeated occurrences of hours on various evenings during which the grid was at its limit and on several occasions had been on the verge of a large-scale collapse. Had just one large line shut down due to overload during these times, a deluge of shutdowns and power outages might have been unavoidable. Moreover, on 18 January 2017, three days prior to the start of the ten-day dark doldrums in Germany, his company had written to the Federal Ministry for Economic Affairs and Energy and the Federal Network Agency, warning them of the temporary loss of (n-1) secure grid control. At the latest when the nuclear power plants in southern Germany cease to operate, high power transmission requirements will become the norm. The necessary grid expansion must therefore be pushed ahead with rapidly.

## Summary

VGB PowerTech has carried out a plausibility check of electricity generation from wind power in Germany and 17 neighbouring European countries and in the process explored questions as to whether adequate possibilities for mutual balancing exist within the interconnected European grid true to the motto "the wind is always blowing somewhere".

In the current energy policy environment which, against the backdrop of the international climate protection commitments facing Germany, seeks to abandon the power plant technology proven over decades and create extensive provision of electricity from renewable energies, photovoltaics and wind power remain the only scalable technologies capable of further development for the Energiewende in the short to medium term. However, they are always reliant on complementary technologies.

Looking back at the past year in Germany, it can be concluded that additional operating experience confirms the statements made in the first part of the VGB Wind Study: from the perspective of security of supply, wind power, despite concerted efforts to expand since 2010, has for all practical purposes not replaced any conventional power plant capacity. Furthermore, offshore wind power at its current level of development is shown to be not capable of serving as a reliable source of baseload power and cannot replace conventional power plant capacity. Wind turbine locations spread throughout Germany are not a solution for a reliable and secure supply of electricity. Dispatchable complementary technologies are always necessary in conjunction with wind power.

From a European perspective, it can be concluded on the basis of 18 countries observed here that although statistically significant smoothing effects are to be seen, these only help to a limited extent when it comes to security of supply: 4 to 5 % of the nominal capacity means with consideration of unavoidable grid losses that, even at a European level, dispatchable backup capacity of almost 100 % of the nominal capacity of all European wind turbines has to be maintained, as long as this has not yet exceeded the annual peak load in Europe plus reserves.

## Acknowledgements

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## Literature

1. Linnemann, Th.; Vallana, G. S.: Wind energy in Germany and Europe: Status, potentials and challenges for baseload application, Part 1: Developments in Germany since 2010. VGB PowerTech 97 (2017), No. 8, pp. 70 bis 79.
2. Linnemann, Th.; Vallana, G. S.: Wind energy in Germany and Europe: Status, potentials and challenges for baseload application, Part 1: Developments in Germany since 2010. atw 62 (2017), No. 11, pp. 678 to 688.
3. Weber, H.: Versorgungssicherheit und Systemstabilität beim Übergang zur regenerativen elektrischen Energieversorgung. VGB PowerTech 94 (2014), No. 8, pp. 26-31.
4. Bericht der deutschen Übertragungsnetzbetreiber zur Leistungsbilanz 2016 bis 2020. Version 1.1 dated 30 January 2018. www.netztransparenz.de
5. BMWi-Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland von 1990 bis 2016. www.erneuerbare-energien.de
6. Arbeitsgemeinschaft Energiebilanzen (AGEB): Bruttostromerzeugung in Deutschland ab 1990 nach Energieträgern. www.ag-energiebilanzen.de
7. BDEW: Stromerzeugung und -verbrauch 2017 in Deutschland. BDEW-Schnellstatistik dated 14 February 2018. www.bdew.de
8. Bundesnetzagentur: Monitoringbericht 2017. www.bundesnetzagentur.de
9. Wagner, F.: Surplus from and storage of electricity generated by intermittent sources. European Physical Journal Plus 131 (2016): 445. https://epjplus.epj.org DOI 10.1140/epjp/i2016-16445-3
10. Wagner, F.: Überschussstrom und Stromspeicherung unter den Bedingungen intermittierender Produktion. Tagungsband zur Frühjahrssitzung des Arbeitskreises Energie der Deutschen Physikalischen Gesellschaft (DPG), Münster, 2017, pp. 54 to 74. www.dpg-physik.de/veroeffentlichung/ake-tagungsband/tagungsband-ake-2017.pdf
11. VDE-Infoblatt Störungsstatistik 2016. www.vde.com
12. Wagner, F.: Considerations for an EU-wide use of renewable energies for electricity generation. Eur. Phys. J. Plus 129 (2014): 219. https://epjplus.epj.org DOI 10.1140/epjp/i2014-14219-7
13. Rodriguez, R. A. et al.: Transmission needs across a fully renewable European power system. Renewable Energy, 63 (2014), pp. 467 to 476. DOI 10.1016/j.renene.2013.10.005
14. ENTSO-E Transparency Platform. https://transparency.entsoe.eu
15. Vaughan, A.: UK summer wind drought puts green revolution into reverse. Article dated 27 August 2018. www.theguardian.com
16. BP Statistical Review of World Energy 2018 – data workbook: www.bp.com
17. 50 Hertz, www.50hertz.com
18. Amprion, www.amprion.net
19. Tennet TSO, www.tennet.eu
20. Transnet BW, www.transnetbw.de
21. EEX Transparency, www.eex-transparency.com
22. Online database on the global wind power market: www.thewindpower.net
23. Buttler, A.; Dinkel, F.; Franz, S.; Spliethoff, H.: Variability of wind and solar power. An assessment of the current situation in the European Union based on the year 2014. Energy 106 (2016), pp. 147 to 161. DOI 10.1016/j.energy.2016.03.041
24. Grams, C. M. et al.: Balancing Europe's wind-power output through spatial development informed by weather regimes. Nature Climate Change 7 (2017), pp. 557 to 562, DOI 10.1038/nclimate3338.
25. Becker, P.: Wetterbedingte Risiken der Stromproduktion aus erneuerbaren Energien durch kombinierten Einsatz von Windkraft und Photovoltaik reduzieren. Deutscher Wetterdienst (DWD), 6 March 2018, Berlin. www.dwd.de
26. Baïle, R.; Muzy, J.-F.: Spatial Intermittency of Surface LayerWind Fluctuations at Mesoscale Range. Physical Review Letters 105 (2010), pp. 254501-1 to 254501-4. DOI 10.1103/PhysRevLett.105.254501
27. Wilms, J.: Das SüdLink-Projekt. Technische Optionen für eine Hochspannungsgleichstromübertragung. Dialogue procedure for the SüdLink project Brunsbüttel-Großgartach on 21 May 2015 in Schwäbisch-Hall.
28. Krontiris, A.: Von HGÜ zu UHGÜ. Entwicklungen und Perspektiven in der großräumigen Gleichstromübertragung. Vortrag zur Herbstsitzung des Arbeitskreises Energie der Deutschen Physikalischen Gesellschaft (DPG), Bad Honnef, 20 October 2017
29. CEER Report on Power Losses. Reference C17-EQS-80-03, www.ceer.eu
30. U.S. Energy Information Administration: www.eia.gov/beta/international
31. Energy performance report 2015 of the German transmission system operators pursuant to EnWG § 12(4) and (5). Updated in February 2016, www.netztransparenz.de
32. European Commission: EU energy in figures. Statistical pocketbook 2017. https://ec.europa.eu/energy/en/data-analysis/energy-statistical-pocketbook
33. Lüers, S.; Wallasch, A.-K.; Rehfeldt, K.: Kostensituation der Windenergie an Land in Deutschland, Update. Varel, 2015, www.windguard.de
34. Hughes, G.; Aris, C.; Constable, J.: Offshore wind strike prices behind the headlines. Global Warming Policy Foundation Briefing 26, 2017, www.thegwpf.org
35. Hirschhausen, C. et al.: Europäische Energiewirtschaft. Hoher Investitionsbedarf für Nachhaltigkeit und Versorgungssicherheit. DIW-Wochenbericht No. 27, 2014.
36. ENTSO-E Ten-year network development plan 2012. www.entsoe.eu
37. Hughes, G.: The Performance of Wind Farms in the United Kingdom and Denmark. Renewable Energy Foundation, 2012. www.ref.org.uk
38. Wolff, R.: Haltbarkeit von Windkraftanlagen. Erodierende Rotoren. taz edition dated 5 March 2018. www.taz.de
39. Schürmeyer, J.: Windpark Alpha Ventus vor Borkum. Abgestürzte Windpark-Gondel vor Austausch. NWZ online edition dated 27 July 2018. www.nwzonline.de
40. Milan, P.; Wächter, M.; Peinke, J.: Turbulent character of wind energy. Physical Review Letters 110 (2013), pp. 138701-1 to 138701-5. DOI 10.1103/PhysRevLett.110.138701
41. Peinke, J.; Heinemann, D.; Kühn, M.: Windenergie – eine turbulente Sache? Physik Journal 13 (2014) No. 7, pp. 35 to 41.
42. Anvari, M.; Lohmann, G.; Wächter, M. et al.: Short term fluctuations of wind and solar power systems. New Journal of Physics 18 (2016) 063027, pp. 1 to 14. DOI 10.1088/1367-2630/18/6/063027
43. Schmietendorf, K.; Peinke, J; Kamps, O.: On the stability and quality of power grids subjected to intermittent feed-in. https://arxiv.org/abs/1611.08235
44. Laux, M.: Redispatch in Deutschland. Evaluation of transparency data, April 2013 to January 2018. www.bdew.de
45. Bundesnetzagentur: Quartalsbericht zu Netz- und Systemsicherheitsmaßnahmen für das dritte Quartal 2015. www.bundesnetzagentur.de
46. Mihm, A.: Energiewende, Stromnetz kurz vor dem Zusammenbruch. FAZ edition dated 9 June 2017. www.faz.net

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