Wind energy in Germany and Europe

Status, potentials and challenges for baseload application

Part 1: Developments in Germany since 2010

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Kurzfassung

Windenergie in Deutschland und Europa Status quo, Potenziale und Herausforderungen in der Grundversorgung mit Elektrizität Teil 1: Entwicklungen in Deutschlandseit 2010

Die installierte Nennleistung sämtlicher Windenergieanlagen in Deutschland hat sich in den letzten 16 Jahren, von Anfang 2001 bis Ende 2016, auf 50.000 Megawatt (MW) verachtfacht. In 18 betrachteten europäischen Ländern, die Windenergie heute nutzen, erhöhte sich die Nennleistung im gleichen Zeitraum um das Zwölffache auf mehr als 150.000 MW.

Eine wesentliche physikalische Eigenschaft der Windenergie ist ihre starke raumzeitliche Variation aufgrund der Fluktuationen der Windgeschwindigkeit. Meteorologisch betrachtet wird die aus Windenergieanlagen eingespeiste elektrische Leistung durch Wetterlagen mit typischen Korrelationslängen von mehreren hundert Kilometern bestimmt. Im Ergebnis ist die aufsummierte eingespeiste Leistung der europaweit über mehrere tausend Kilometer sowohl in Nord-Süd- als auch Ost-West-Richtung verteilten Windenergieanlagen hoch volatil, gekennzeichnet durch ein breites Leistungsspektrum.

Die intuitive Erwartung einer deutlichen Glättung der Gesamtleistung in einem Maße, das einen Verzicht auf Backup-Kraftwerksleistung ermöglichen würde, tritt allerdings nicht ein. Das Gegenteil ist der Fall, nicht nur für ein einzelnes Land, sondern auch für die große Leistungsspitzen und -minima zeigende Summenzeitreihe der Windstromproduktion 18 europäischer Länder.

Für das Jahr 2016 weist die entsprechende Zeitreihe (Stundenwerte) bei idealisiert verlustfreier Betrachtung einen Mittelwert von 33.000 MW und ein Minimum von weniger als 6.500 MW auf. Dies entspricht trotz der europaweit verteilten Windparkstandorte gerade einmal 4 % der in den betrachteten 18 Ländern insgesamt installierten Nennleistung.

Windenergie trägt damit praktisch nicht zur Versorgungssicherheit bei und erfordert 100 % planbare Backup-Systeme nach heutigem Stand der Technik.

Da das benötigte Speichervolumen aller heute bekannten Speichertechnologien im Vergleich zur Elektrizitätsnachfrage gering ist (auch in Kombination und mit steigender Tendenz bei weiterem Ausbau volatiler, vom Dargebot abhängiger erneuerbarer Energien), müssen konventionelle Kraftwerke diese Backup-Funktion übernehmen. Deren Rentabilität steht ohne Kapazitätsmärkte schon heute in Frage.

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The nominal capacity of all wind turbines in Germany has increased eightfold over the last 16 years, from early 2001 to the end of 2016, to 50,000 megawatts (MW). In 18 European countries considered in this study using wind energy today, over the same period the nominal capacity, also referred to as nameplate capacity or rated capacity, rose by a factor of twelve to more than 150,000 MW.

One essential physical property of wind power is its large spatiotemporal variation due to wind speed fluctuations. From a meteorological point of view, the electric power output of wind turbines is determined by weather conditions with typical correlation lengths of several hundred kilometres. As a result, the total power output of the wind power plants distributed across Europe over several thousand kilometres in north-south and east-west direction is highly volatile and exhibits a strong intermittent character.

An intuitively expectable significant smoothing of this wind fleet power output to an amount which would allow a reduction of backup power plant capacity, however, does not occur. In contrast, a highly intermittent wind fleet power output showing significant peaks and minima is observed not only for a single country, but also for the whole of 18 European countries considered.

For 2016 the relevant cumulative time series (hourly resolution) shows a mean value of 33,000 MW and a minimum of less than 6,500 MW. Despite widespread distribution of wind turbine locations all across Europe, this is equivalent to a mere 4 % of the cumulative nominal capacity of wind turbines in these 18 countries.

For practical purposes, therefore, wind power does not contribute to security of supply and requires 100 % predictable backup systems based on state-of-the-art power plant technology to meet the maximum load.

VGB PowerTech, hereinafter referred to as VGB in short, has explored questions of electricity generation from wind power in Germany and 17 neighbouring European countries and carried out a plausibility check.

This plausibility check is based on publicly accessible time series data of electric power supplied by wind turbines distributed widely over 18 European countries, as published by national and European transmission system operators.

The VGB Wind Study 2017 consists of two parts. The first part deals with long-term developments in Germany from 2010 to 2016. The second part discusses electricity generation from wind power in 18 European countries in 2016 and explores whether adequate possibilities for mutual balancing exist within the interconnected European grid according to the slogan “wind is always blowing somewhere”.

Introduction

In view of international climate protection obligations the German federal government is pursuing an ambitious reorganisation mainly of electricity supply, referred to as “Energiewende”[1]. This restructuring project involves an abandonment of well-established power plant technology that has worked effectively for many decades, and aims at the provision of electricity from renewable energy sources.

As a result of these energy policy targets there is a lack of alternatives for power plants for demand-driven baseload application as well as a lack of usable energy sources due to the current concentration on solar energy (photovoltaics) and wind power as big white hopes[2] for the “Energiewende”:

[1] The German concept termed “Energiewende”, in English usually referred to as energy transition, actually must be understood as an electricity transition: Electric energy today accounts for only 21 % of final energy consumption in Germany; the primary energy used for this purpose in power plants accounts for 31 % of Germany’s primary energy consumption, so that even upon complete implementation of this “Energiewende” Germany only will have covered a modest part of the overall route [1, 2].

[2] In general, renewable energy sources suffer from an intrinsic and crucial drawback: Their energy density is by about two orders of magnitude less in comparison to fossil fuels (and even five to nuclear), thus increasing by a factor of hundred (hundred thousand) the technical, material-based, spatial and financial efforts to make the requested electric noble energy reliably available at the wallplug.

Nuclear energy, like **lignite** and **hard coal**[3], is undesirable in Germany from an energy policy point of view.

Natural gas is regarded at best as a bridging technology in view of Germany's climate protection endeavours, since its combustion also produces carbon dioxide and its use methane emissions, albeit to a lesser degree than other hydrocarbon-based fuels. A further aspect: If use of natural gas as primary energy source would be reinforced in future in the electricity sector also – today it is used mostly for process heat and heating purposes and as raw material in the chemical industry – Germany's today's already strong dependence on imported energy would increase further. Other drawbacks are high cost, lack of natural gas storage facilities for this additional purpose, and lack of public acceptance concerning fracking technologies necessary for an expansion of domestic natural gas production.

Biomass is limited, favours development and expansion of monocultures with foreseeable repercussions for biodiversity in case of unsustainable agriculture and forestry and competes with exploitation of biofuels, basic chemicals and food production (ethical issues). From a scientific viewpoint biomass must be available in future preferably for the supply of synfuels to Germany.

Hydropower is also limited. Already being well-established and applied largely in all of Germany, its potential for further expansion is limited and, for the most part, today virtually exhausted.

Geothermal energy, compared with steam cycles of conventional power plants, exhibits appreciably lower temperature levels and, at best, reasonably can be considered for the purpose of electricity generation only in certain regions of Germany, using fluids other than water[4]. Its potential for expansion is extremely limited, and its contribution to power supply is likely to remain small within the foreseeable future.

Other options like **landfill gas, sewage gas, mine gas** or **domestic waste** (**biogenic fraction**) today contribute with about 5 % to Germany's power supply. Their potential for expansion also is likely to be limited.

Given the current energy policy and regulatory environment, therefore, for all practical purposes only solar energy (photovoltaics) and wind energy remain open for further reinforced development as technologies for the German "Energiewende" target.

Solar energy alone, however, is insufficient and requires complementary technologies to bridge times of day and night when solar radiation is available only on a small scale or not at all: During the day – under a thick cloud cover, for example – the contribution of photovoltaics to electricity supply can be very strongly restricted, whereas at nighttime no contribution is possible. In winter months, moreover, photovoltaics make appreciably smaller contributions to electricity supply than during summer months.

Wind energy as volatile and intermittent regenerative energy alone likewise is insufficient, because of its unsteady availability. One essential physical property of wind power is its large spatiotemporal variation due to wind speed fluctuations. From a meteorological point of view, the electric power fed into the grid by wind turbines is determined by weather conditions with typical correlation lengths of several hundred kilometres. As a result, the electric power output of wind turbines distributed widely over Germany is highly volatile and exhibits a strong intermittent character, with significant peaks and minima. For secure and reliable electricity supply, both supply-dependent wind power and photovoltaics are dependent on complementary technologies that must be able to step in during dark calms.

In principle, conventional fossil-fired power plants, nuclear power stations or pumped storage power plants come into question as complementary technologies for this backup function today.

However, nuclear power plants, lignite-fired and hard-coal-fired power plants are no longer politically desirable in Germany, and natural-gas-fired power plants as bridging technology are politically acceptable for limited periods at best, since they still continue to release carbon dioxide and would further increase the already high dependence on imported natural gas.

Though expansion of pumped storage power plants, tried and tested in decades of operation – and the only storage technology available to date on an industrial scale – would be desirable, on account of topographic conditions in Germany this is possible only to a very limited extent and often meets with acceptance problems, especially in the local population, owing to the visible intrusion on the environment caused by the construction of reservoirs.

A further aspect: Today's pumped storage power plants always had been designed for requirements of conventional power plants and peak load levelling on short call in the course of the day[5]. For the seasonal balancing in future, pumped storage power plants with large reservoirs for working volumes in the single- to double-digit terawatt-hour (TWh) range would be required, several hundred times more than we have today. The crucial question is whether large-scale plants designed for seasonal balancing purposes could be profitably operated at all.

In turbine mode, with a complete discharge cycle of about six hours, all pumped storage power plants in Germany together can deliver an electric output of around 7,000 MW and supply around 0.04 TWh of energy. After that the upper water reservoirs first must be refilled in pump mode, involving consumption of electricity. Here an example to show prospects for the post "Energiewende" future in Germany: Merely to bridge a two-week weak wind phase ("dark doldrums"), not uncommon in this country, in the winter half-year some 21 TWh would have to be made available by a backup system[6] to meet the power requirements.

Were these 21 TWh to be covered by pumped storage power plants with an average capacity of about 200 MW[7] through six hours of turbine operation as possible maximum, 17,500 additional plants of this size would be needed. Compare: Germany's currently largest pumped storage power plant, Goldisthal in Thuringia, with a nominal capacity of 1,060 MW in turbine mode, delivers around 0.009 TWh of electricity over a maximum period of eight hours when required. Comparably favourable topographic locations are rare in Germany, however.

The occasionally publicised chemical conversion process of water electrolysis with downstream methanation of the hydrogen gas through the addition of carbon dioxide, also called power-to-gas method, must be termed "energy dissipation" and not energy storage process when subjected to serious assessment: In pumped storage power plants about 25 % of the input energy is lost, so that after storage 75 % is available as effective energy. In the multi-stage power-to-gas conversion process, however, from water electrolysis through methanation and storage in the gas network to use as fuel in gas-fired power plants, losses of at least four-fifths of the electric energy input must be expected if the intermittent operating regime, the origin of carbon dioxide and the energy for its

[3] This statement also holds true – for lack of public acceptance – for power plant technologies employing carbon dioxide capture from flue gas with subsequent underground storage of carbon dioxide.

[4] Owing to the small temperature difference between heat source and heat sink, organic fluids with relatively low boiling temperatures are frequently used. Therefore, such cycles also are referred to as Organic Rankine Cycles (ORC).

[5] Demand peaks occur around midday and in early evening hours. At late night the demand for electricity regularly is at its lowest.

[6] Given a domestic total electricity consumption (including grid losses) of about 550 TWh annually, the average daily requirement to be covered is 1.5 TWh.

[7] Equivalent to the average turbine electric power output of German pumped-storage power plants.

supply for the methanation step are seriously factored in [3]. The cost of the electric output energy in these cases must be at least five times higher than the cost of the electric input energy.

Here an example to illustrate the consequences: For each EEG-subsidised[8] electric kilowatt-hour (kWh) from wind power, in the past year 2016 an average allocation of 9 €Ct/kWh was charged. The market price obtained was 2 €Ct/kWh, so that non-privileged end consumers in Germany had to foot the additional cost of 7 €Ct/kWh [4].

One kilowatt-hour of electric output energy from an efficiently operated power-to-gas plant using wind power as electric input energy accordingly would have to cost at least 45 €Ct/kWh. That includes neither the necessary profit of the power-to-gas plant operator, nor the network charges, taxes and other government levies (excluding EEG levy), for which alone an average household with an annual requirement of 3,500 kWh had to pay almost 57 % of the end customer electricity price in Germany in the past year [1].

Points in favour of the power-to-gas process are the more than 200 TWh of energy that can be stored in the German gas network and the diverse sectoral applications. However, it must be noted that the current infrastructure with pipes and underground gas storage facilities has been designed for the needs of today's gas consumers, so that significant expansion would be indispensable for any extended use of this infrastructure as backup system for balancing wind energy and photovoltaics.

Leaving the considerable conversion losses and the associated economic effects out of account, obtaining the quantities of energy needed for balancing intermittent renewable energy systems (iRES) such as wind power and photovoltaics through chemical storage in hydrocarbons could be possible from a technical viewpoint: Widening our view to include other sectors such as transport (fuels), households, industry, commerce, trade and services (heating and process heat), synthesised methane or methanol (fuel) could be applied in a useful way also in many other areas. This might help explain the recently observed hyping of "sector coupling"[9] by federal ministries, the public and the media in Germany.

The crucial question is whether the German population is willing and able to actually bear the added economic and personal consequences[10] entailed by sector coupling when their magnitude becomes visible and they impact the everyday life of citizens.

Other options discussed as alternative to the building of the required backup systems are the reduction (efficiency improvements) and control of final energy consumption (load management). Considering the trend of gross electricity consumption in Germany in the past 16 years, which has increased by an average of 0.2 % annually on substantial efforts to improve efficiency, and in view of strategies for the future that call, for example, for expanding electric mobility or use of electrically operated heat pumps, which would cause demand for electricity to rise further, it seems advisable to stress the need for more realism, especially as regards the willingness of the population to embrace a basic behaviour oriented to sufficiency.

Other storage options discussed by the public and in the media, such as batteries, electric mobility, concrete spheres on the seafloor or ringwall pumped hydro storage systems, generally fail to appreciate the dimensions of the energy quantities that will have to be stored and withdrawn in future and the technical challenges involved in this. They will not be available in the foreseeable future, neither on the required scale nor at economically reasonable cost, so that the conventional power plant fleet will have to continue exercising the necessary backup function.

Due to the legal feed-in priority for renewables and the increasingly poorer capacity factor of the required backup systems (currently conventional power plants) which the expansion of renewables entails, in many cases the economic efficiency of these backup systems has been called into question in Germany. In other words: The German "Energiewende" is characterised by a dual structure. It consists of a growing fleet of renewables that require the expansion of electricity grids at all voltage levels, and a conventional backup power plant fleet with practically the same capacity as the present conventional power plant fleet[11] to ensure the security of supply, however with declining capacity factors.

In 2016 wind power and photovoltaics contributed around 116 TWh or 21 % to the electricity consumption of 550 TWh (including grid losses) in Germany.

During implementation of the "Energiewende" based on the current conditions, focus is on the intermittent renewable energy systems (iRES) wind power and photovoltaics.

Analyses of Germany's power supply postulating an iRES share of 100 % on the basis of a defined annual electricity supply of 500 TWh show [5 to 8] that, for this purpose, an installed iRES nominal capacity averaging 330,000 MW would have to be built up[12]. About a quarter of this electricity supply at least would be surplus energy. In addition, from year to year weather-induced fluctuations of this electricity supply by around ±15 % would have to be taken into account.

To guarantee security of supply, and for the purpose of combined assessment, backup capacities of about 89 % of the annual peak load in Germany would have to be kept in reserve, if 500 TWh of iRES electricity should be delivered completely by onshore wind power, offshore wind power and photovoltaics annually.

Further analyses [1] concerning storage of volatile electric power output from wind power plants and photovoltaic systems in Germany provide additional indications of the immensity of these challenges.

The current practice in Germany of managing a capacity market "behind closed doors", where the Federal Network Agency assesses conventional power plants for which closure notifications are submitted as systemically relevant from the viewpoint of power grid stability and apportions the cost of maintaining these power plants to all end consumers through additional network charges, appears to be a highly questionable approach. Instead of government intervention, and in the interest of consumers, a return to competition and cost efficiency would be advisable here, for example through a competitive capacity market.

On top of this, even today the German electricity supply system can operate with stable grids only through a supply-dependent temporary export of substantial surplus power, more and more often at negative electricity prices, as for example on 26 December 2016, with 15 GW. As soon as Germany's immediate neighbours achieve a similar level of intermittent renewable energy sources, this option no longer will be available.

In any consideration of Germany's electricity supply, security of supply must be the centre of interest[13], because production and consumption of electricity always must be kept strictly in balance in order to avoid power failures.

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8 EEG: Erneuerbare-Energien-Gesetz, German Renewable Energy Sources Act.

9 The joint consideration and interlinkage of three energy industry sectors – electricity, heat supply and transport – is referred to as sector coupling.

10 Examples of possible consequences are: supply-dependent use of electric energy or even higher electricity prices for private households than today (in Europe today Germany ranks second, electricity prices are higher only in Denmark).

11 Including the necessary reserve required to ensure the defined level of supply security.

12 For comparison: At year-end 2016 in Germany an iRES nominal capacity of about 90,000 MW was installed.

13 Other energy industry target criteria are economic efficiency, environmental safety and acceptance.

Against this backdrop, in June 2015 the Federal Ministry for Economic Affairs and Energy (BMWi) announced the beginning of a new era in the security of supply and stated publicly [9] that in future Germany would cooperate even more closely with its European neighbours in the area of electricity supply. The cross-border exchange of electricity, the ministry said, helps to ensure reliable, cost-efficient supply in the event of consumption peaks and lulls in electric power output, for example because the wind is not blowing or the sun is not shining. According to the ministry, experience shows that the highest demand for electricity does not occur simultaneously in the countries, and the wind is almost always blowing somewhere in Europe. It is about real synergies, says the ministry: Less secured capacity would be required in the regional network; the interconnected grid system would make substantial cost savings possible.

In contrast, an article in the magazine Energiewirtschaftliche Tagesfragen in December 2015 [10] called into doubt statements frequently made in public and in the media on the effect that further expansion of wind power would lead to the smoothing of the electric power output of the German wind fleet and would enable shutting down conventional power plant capacities. The article states: The power output peaks of the German wind fleet[14] have risen continually as a result of the post-2010 expansion, while the annual power output minima remained unchanged in the range of about 100 MW, despite of the extraordinary growth in nominal capacity. In reality, based on the correlation of the electric power output from wind turbines distributed all across Germany, no smoothing can be detected, and further increasing fluctuations can be expected from ongoing expansion of wind power.

VGB took these publications as an opportunity to investigate these and other statements about wind power in Germany and 17 neighbouring European countries and to carry out fact checks and plausibility analyses. The considerations are based on freely accessible data on the cumulative electric power supplied by wind turbine fleets of different countries published by national and European transmission system operators via internet.

The VGB Wind Study 2017 consists of two parts. The first part deals with long-term developments in Germany from 2010 to 2016. The second part discusses current operational characteristics of wind power in 18 countries of Europe in 2016 and explores whether adequate possibilities for mutual balancing exist within the interconnected European grid, according to the slogan “wind is always blowing somewhere”.

[14] In this article the term “German wind fleet” invariably is understood to be the total of all wind turbines in Germany.

VGB Wind Study 2017

A detailed presentation of main results of the VGB study on the status of wind energy in Germany and Europe as well as potentials and challenges for baseload application is retrievable in slide form from the VGB website:

Part 1: Developments in Germany since 2010

Part 2: European situation in 2016

Methodology

Starting point of the VGB analyses were transparency data, accessible in the internet, from the Association of European Transmission System Operators ENTSO-E[15] and the German transmission system operators 50 Hertz Transmission, Amprion, Tennet TSO and Transnet BW as well as the Leipzig EEX[16] market [11 to 16]. Through these transparency platforms, time series for the cumulative electric power output of different power plant types, including photovoltaic systems, onshore wind turbines and offshore wind turbines, as well as for consumer demand (load), in quarter-hourly to hourly resolution, are retrievable.

The Association of European Transmission System Operators ENTSO-E rebuilt its transparency platform at the beginning of 2015 and time-synchronised all transparency data, an important factor in the chronologically correct overlaying of time series for individual countries and in making analyses of the balance at any one moment between consumption (load) and generation.

The restructured ENTSO-E transparency platform thus enabled consistent retrieval of the data points of countries covered there based on Coordinated Universal Time, UTC[17].

Since time series data of individual countries covering several years were not available there, the evaluation of wind power in Germany from 2010 to 2016 was made on the basis of data provided by the German transmission system operators and the EEX transparency platform.

The data points (quarter-hourly values) retrieved there for the electric output of domestic onshore and offshore wind power plants represent projections based on a limited number of measured reference locations [13].

In the aggregate, the evaluation of wind power in Germany over several years was based on around five million data points.

[15] ENTSO-E: European Network of Transmission System Operators

[16] EEX: European Energy Exchange

[17] UTC: Coordinated Universal Time

To examine the completeness of these time series the following cases had to be taken into account:

- Data points with very low power outputs close to 0 MW that remained unchanged or single missing data points that were interpolated when directly adjacent data points also showed comparably low values (criterion of high plausibility for a weak wind phase or lull).
- Missing data points with directly adjacent data points showing power outputs well above several hundred to a thousand megawatts. Such gaps occurred in 0.1 % of all data points. In these cases the missing data points were corrected using the arithmetic mean of the adjacent data points (criterion of high plausibility for incorrect value).
- Continuous gaps over several quarter-hours, hours or days. Such gaps occurred in 0.01 % of all data points. These gaps were corrected alternatively either by linear interpolation (small gaps) or based on data of comparable weekdays in directly adjacent weeks.

This first step was followed by a second review and plausibility verification step. It encompassed a comparison of integrated annual power output, as computed from individual time series, with the energy industry statistics available for Germany from the Working Group on Energy Balances (AGEB) [2], the Federal Ministry for Economic Affairs and Energy (BMWi) [17, 18], the German Association of Energy and Water Industries (BDEW) [4] and the German Wind Energy Association (BWE) [19].

In order to analyse electricity generation from wind power in Europe in 2016, for retrieval of the data from the ENTSO-E transparency platform it was decided to use the ranking of the 18 most important countries by nominal capacity, with largely intact time series, here in alphabetical sequence: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Romania, Sweden, Spain and United Kingdom.

In the subsequent data evaluation, because of the short period of one year, compared with Germany, only about 1.2 million data points had to be examined and checked for plausibility.

The same procedure as for Germany was used to review the data. The energy industry statistics of the BP Statistical Review of World Energy 2017 provided the basis for reviewing the time series and verifying their plausibility [20].

Results

Analysis results of wind power production in Germany from 2010 to 2016 are presented below. The results for wind power production in 18 countries of Europe in 2016 will be the subject of a further article [21].

At year-end 2010 the German wind fleet had a cumulative nominal capacity P_N of just about 27,000 MW [18]. Of that total, onshore wind turbines accounted for 99.7 % and offshore wind turbines for 0.3 %.

By year-end 2016 around 19,000 MW onshore nominal capacity and around 4,000 MW offshore nominal capacity had been added, so that the German wind fleet had a total nominal capacity of about 50,000 MW. Onshore wind energy accounted for about 92 % of the total and offshore wind energy for the remaining 8 %.

The time series for the hourly electric power output of the wind fleet in 2016 and the shares accounted for by onshore wind energy and offshore wind energy are shown in Figure 1.

The wind fleet power output shows great fluctuations throughout the entire year. In many hours the fluctuations simultaneously affect onshore and offshore wind power. In addition, pronounced weak wind phases are discernible with the power output of the wind fleet rapidly falling to a few percent of the nominal capacity.

In 2016 the minimum cumulative electric power P_{Min} of 135 MW (hourly resolution, ENTSO-E data) and 141 MW (quarter-hourly resolution, German TSO data) occurred on 24 July 2016. On this summer day throughout seven of 24 hours the wind fleet delivered less than 500 MW, i.e., less than 1 % of the nominal capacity already installed at the start of the year. Similarly low figures over several consecutive hours also can be found in January, May, June, August, September, October and December 2016.

Contrary to statements claiming that offshore wind power basically can be a source of baseload electricity and can replace conventional power plant output, the power output of the offshore wind fleet fell to 1 % of its nominal capacity or less in 2016 in 256 of the 8,784 hours (2015: 290 hours). Such weak wind phases thus occurred last year with an average of five times a week – a circumstance that is important for expanding offshore wind power, as otherwise these wind turbines hardly could be erected at sea.

During pronounced lulls in June and December 2016 the power output of the offshore wind fleet fell at times even to 0 MW. In 2015 there were similar lulls in January and August. This proves that weak wind phases can occur throughout the year, both onshore and offshore.

The continuously available offshore power output in each of the last two years was thus 0 MW. Offshore wind power made no contribution to a secure power supply and practically required 100 % backup by conventional power plants.

Experience shows that the highest cumulative electric power can be observed during

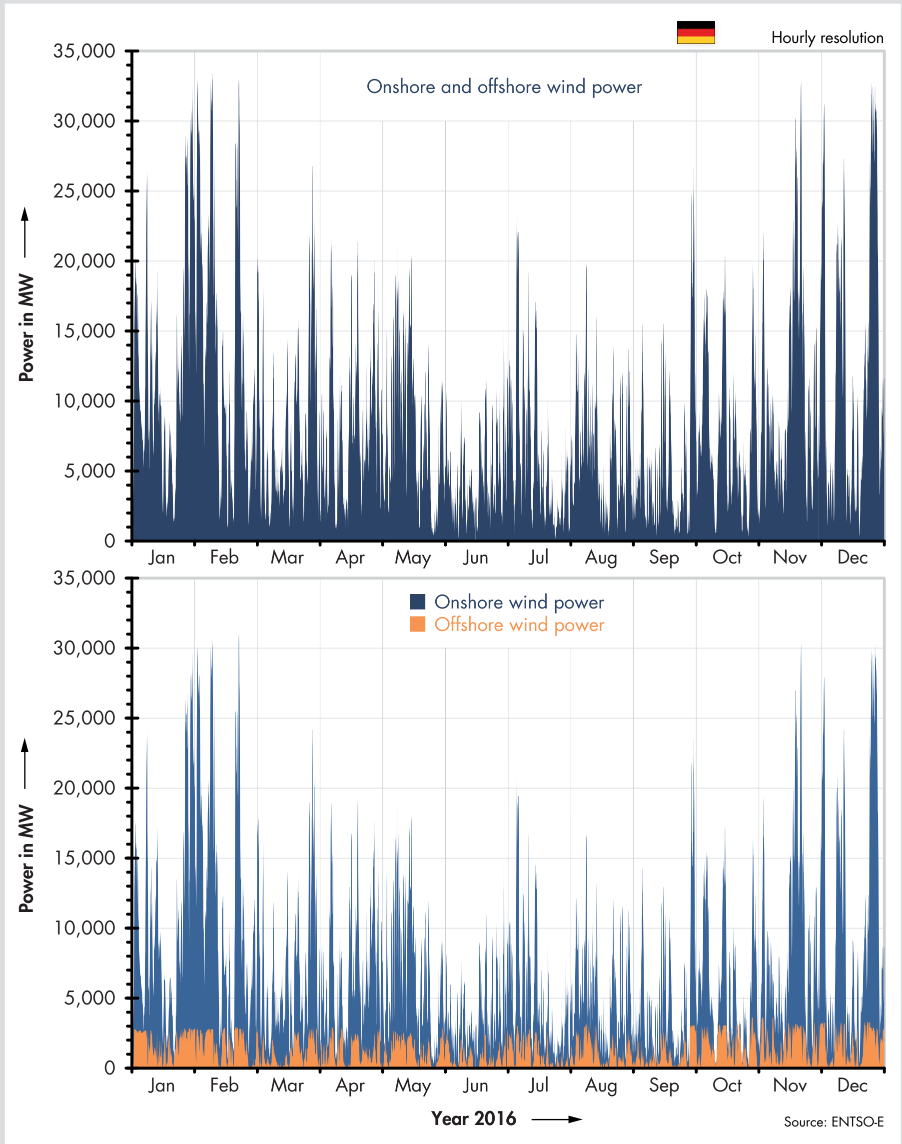

Fig 1. Electricity generation from wind power in Germany (top) and breakdown of onshore and offshore wind power (bottom).

the winter months. The annual maximum electric power P_{Max} of 33,834 MW for the entire German wind fleet was generated in February 2016 and reached the equivalent of just about 75 % of the nominal capacity installed at the start of the year. Similarly high power output figures over several consecutive hours also were recorded in November and December 2016.

From the time series of hourly cumulative electric power output figures of the German wind fleet shown in Figure 1, a total annual production of 76.9 TWh can be computed. By comparison, the Working Group on Energy Balances (AGEB) reports an annual value of 77.4 TWh for German electricity generation based on wind energy [2]. The annual values diverge from each other only by 0.6 % and are thus plausible.

Figure 2 shows relevant figures for the development of wind power in Germany from 2010 to 2016. According to these figures, the cumulative nominal capacity of the German wind fleet of 26,903 MW at year-end 2010 had almost doubled by year-end 2016. The number of wind turbines, at year-end in each case, increased at the same time from 21,600 to 28,200 units (rounded).

The average nominal capacity of every newly added onshore wind turbine in 2010 was 2.0 MW. By 2016 this average had risen to 2.8 MW (offshore wind energy: 5.2 MW per plant).

Apart from the cumulative nominal capacity of the German wind fleet, Figure 2 shows annual maxima P_{Max}, annual minima P_{Min} and annual arithmetic means P_{μ} of the relevant time series for the electrical output of the German wind fleet (quarter-hourly resolution, German TSO data).

The first thing catching the eye is that the cumulative electric power output of the German wind fleet in the past seven years consistently reached annual maxima less than what the plants were designed for, in the range of just 68 % to 81 % of the cumulative nominal capacity.

The difference between nominal capacity and annual maximum evidently has in-

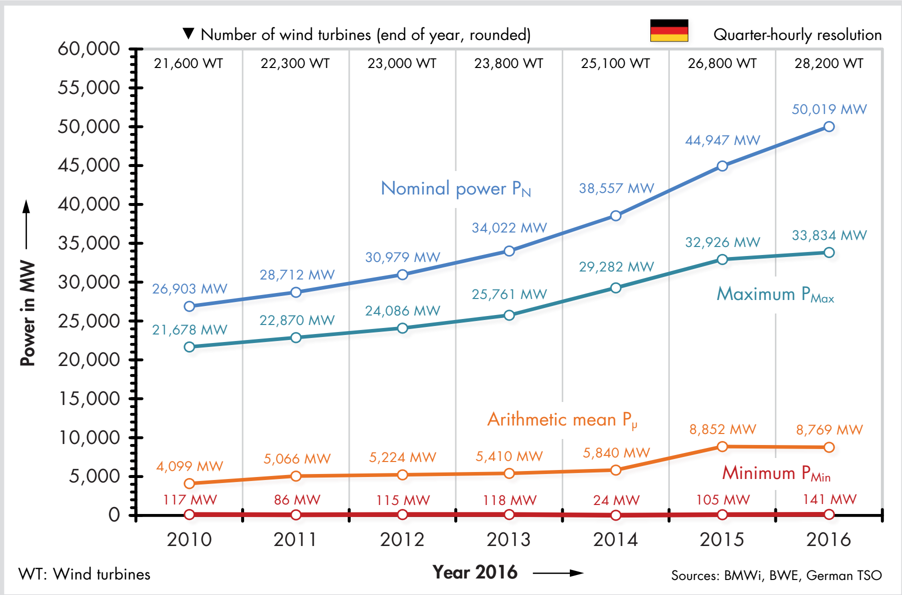

Fig 2. Electricity generation from wind power in Germany from 2010 to 2016.

creased as wind power has expanded. The reasons for this relation are unknown to us. Possibly, as the number of plant locations distributed throughout Germany increases, the probability decreases that peak values will occur simultaneously throughout Germany. A further contributing factor may be that locations with good wind conditions[18] were occupied early on and consequently no longer are available for further expansion, so that it is increasingly necessary to rely on locations with poorer wind conditions.

The arithmetic mean is an equivalent to the energy delivered annually and reflects the constant power output which a power plant with constant operating regime would have to produce in a year to obtain this energy. According to the definition of the arithmetic mean, in the period under consideration all integrated portions of power output above the mean value (surpluses) must yield the same energy as all integrated portions of power output below the mean value (deficit).

The mean values of the time series from 2010 to 2014 rose by an average of 11 % annually to 5,840 MW. For the year 2015, on the other hand, a nearly five times bigger increase of 52 % versus the prior-year value, to 8,852 MW, is recorded. The sharp increase is attributable to a very good wind year with better than average wind conditions [4]: In November and December monthly electricity generation from wind power reached new all-time highs in each month, beyond the never before exceeded mark of 10 TWh. In addition, in eleven of the twelve months of 2015 electricity generation from wind power was higher than in the previous year.

18 Wind locations for high energy yields.

The mean value of the following year 2016 was on a comparably high level at 8,769 MW. However, it must be noted that in this year nearly a third more nominal capacity was available than in 2014 owing to the continual expansion of the German wind fleet, so that it rather should be termed an average wind year. The 10 TWh mark for monthly electricity generation from wind power was not reached again in 2016 despite the growth of nominal capacity.

Two influencing factors were taken jointly into account in the previous considerations: The wind conditions (supply) and the net addition of wind turbines over the course of the year. The question whether the sharp increase in the mean value in 2015 is plausible can be answered by normalisation to a representative nominal capacity for the year concerned. The resultant ratio of average electric power output to potential power output (nominal power) also is referred to as capacity factor η_A. The capacity factor is dimensionless and should be understood as an equivalent to the number of annual hours in which the wind fleet delivered the equivalent of its nominal power. Multiplied by the number of annual hours[19] the result is the full-load hours[20] fraction of the wind fleet in the year concerned.

A comparison of long-term data on the capacity factor of the German wind fleet since 1990 (Figure 3) confirms that in 2015 good wind conditions actually did prevail, and in 2016 average wind conditions [18].

On a long-term average the German wind fleet reports a capacity factor of 16.9 %. The highest figure to date, 21.0 %, was recorded for the year 1993, followed by 20.5 % in 2007 and 20.3 % in 2008. The capacity factor of 19.7 % attained in 2015 is the fourth best value since 1990.

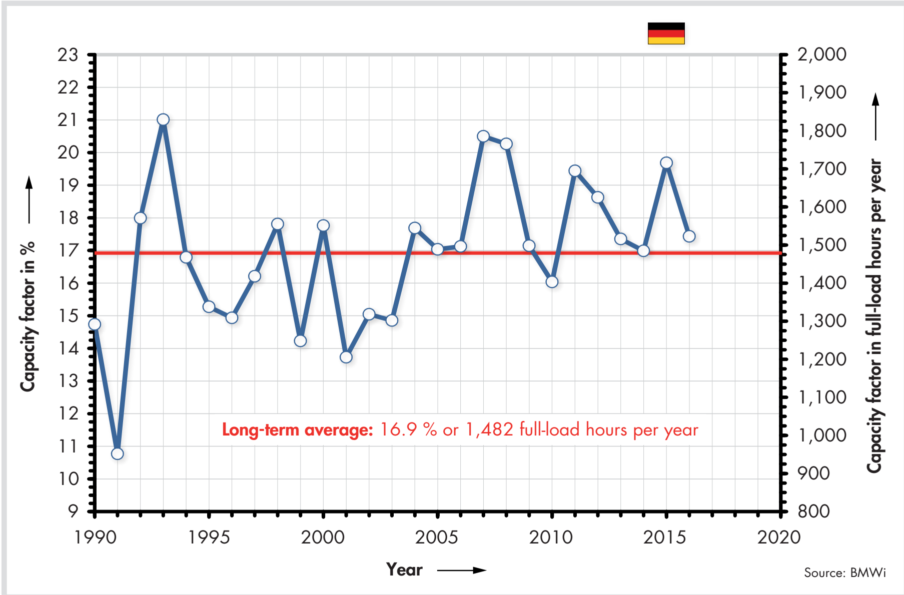

Fig. 3. German wind fleet capacity factors from 1990 to 2016.

From 2010 to 2016 capacity factors reached an average of about 18 %. The annual electricity production of the German wind fleet increased over the same period from 38 TWh to more than 77 TWh [2].

In the overall statistics of the Working Group on Energy Balances (AGEB) on gross power generation in Germany, for the year 2010 we find only inputs from onshore wind power plants. Visible inputs from offshore wind turbines are shown there for the first time for the year 2013 with 0.9 TWh [2]. In the past year 2016, off-

19 A normal year has 8,760 hours,a leap year 8,784 hours.

20 Full-load hours reflect the number of annual hours in which a wind turbine or wind farm would have to operate at its nominal power in order to provide exactly the actually delivered annual energy.

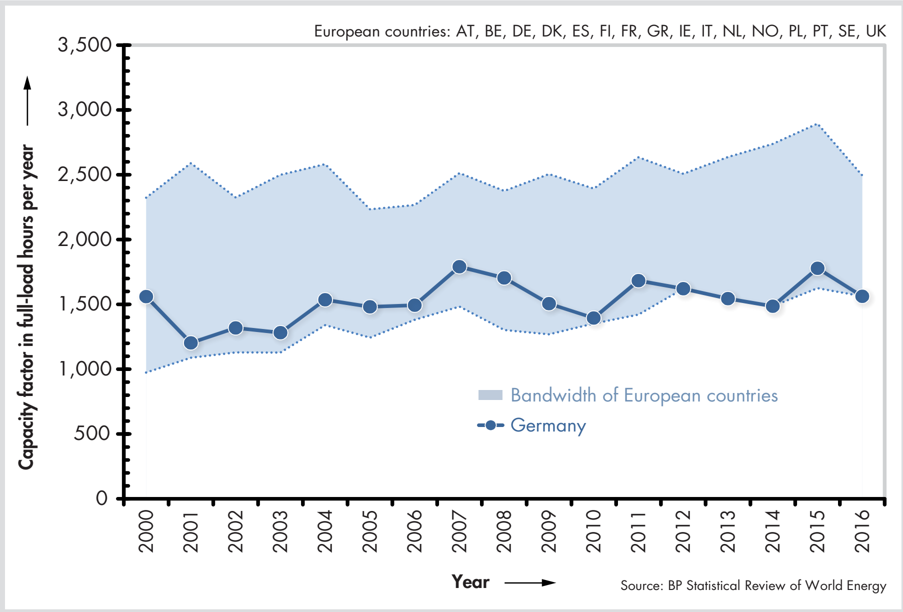

Fig. 4. Efficiency of 2010 to 2016 electricity generation from wind power: Range of capacity factors in Europe and capacity factors in Germany in full-load hours annually.

shore wind power in Germany already delivered more than 12 TWh of electricity, with a capacity factor of 33 %. This is equal to just about 2 % of the gross power production in Germany of 648 TWh.

To answer the question about the role that wind power could play in future baseload application in Germany, it pays to take a look at Europe and the 18 countries examined in this study: There the cumulative nominal capacity, which totalled around 83,000 MW at year-end 2010, likewise nearly doubled by year-end 2016, to around 152,000 MW, while starting from around 148 TWh the annual supply of electricity from wind power has more than doubled to 297 TWh. For comparison: The annual generation of electricity in these European countries today reaches a level of around 3,200 TWh [20, 22]. Wind energy thus holds a share of about 10 % of the electricity production of those countries.

In Figure 4 capacity factors of wind fleets of selected European countries are shown as a spread, overlaid with the capacity factor of the German wind fleet [20].

It is noteworthy that the capacity factor of wind power in many other European countries is significantly higher than in Germany: The average capacity factor of the German wind fleet from 2000 to 2016 is 1,526 full-load hours annually (h/a).

With 2,262 h/a the Irish wind fleet has a 48 % higher capacity factor than the German wind fleet, followed by the UK, Norway and Denmark (+45 %), Greece (+41 %), Spain (+35 %) and Portugal (+33 %).

Other European countries like Finland (+25 %), Sweden (+23 %), Netherlands (+21 %) and Poland (+17 %) as well as Austria (+16 %) and Belgium (+10 %) also achieved a higher average of their wind fleet capacity factors than Germany between 2000 and 2016, whereas the moderate capacity factor of the French wind fleet (+4 %) and that of the Italian wind fleet (+2 %) are comparable with the capacity factors of the German wind fleet.

In anticipation of the second part of the VGB Wind Study 2017 [21] we should mention that the minimum values (hourly resolution) derived for 2016 from time series for the cumulative electric power output from wind power in the aforesaid European countries, and thus the continuously available power outputs, at the same time all were smaller than 1.1 % of the installed nominal capacity in each of these countries. From the viewpoint of security of supply, therefore, there is practically no difference from Germany.

In terms of efficient use of wind power in Europe, Germany is not ideally suited as a wind location (onshore). Since many onshore locations with good wind conditions already have been put to use for wind power in the past decades, today there are fewer such locations in Germany available for further expanding wind power.

However, the nominal capacity of the German wind fleet must still be increased several times over if achievement of the goal of the supply of Germany with electricity largely based on renewables is to remain within reach. This might explain the current efforts of several German states to consider the construction of wind power plants increasingly even in forests, local recreation areas and nature reserves and to push this with building code changes, partly neglecting recognised criteria of species protection, environmental protection and nature conservation on the grounds that the majority of the population approves the implementation of the "Energiewende" [23].

Out at sea (North Sea and Baltic) the wind supply and capacity factors are on the whole better and locations are available for further expansion. Unlike Germany, many other European countries attain a much higher capacity factor with their wind fleets and, taking an objective view of any expansion of wind power in Europe, and for reasons of cost efficiency, actually should be given preference over Germany as locations.

Since offshore wind turbines or wind farms with a typical capacity factor of over 30 % increasingly have been put into service in Germany in the last few years, the long-term average capacity factor of the German wind fleet might increase in future as the offshore wind fleet further expands, despite the high leverage effect of the existing onshore wind power plants.

Regarding the contribution of wind power to security of supply, the development in particular of the annual minima P_{min} of the power output time series, shown in Figure 2, is informative: Since 2010 these values astonishingly have remained at a low average level of 100 MW, even though the nominal power of the German wind fleet has almost doubled in the same period.

Apparently, the intuitive expectation that the annual minimum value will rise with the extension of wind power plant locations all across Germany (true to the motto "the wind is always blowing somewhere") and that the expansion of wind power will enable the substitution of conventional power plant capacities to an increasing degree has not been fulfilled: The expansion during the past seven years has replaced conventional power plant capacities of about 100 MW. Compare: In 2015 the annual peak load occurred on 24 November at 5:30 p.m. and came to 78,200 MW [24].

The continuously available and therefore secured power output of the German wind fleet thus always was significantly less than one percent of its nominal capacity, or, in other words: In every year there was always at least one quarter of an hour in which more than 99 % of the nominal power of the German wind fleet was not available and, for all practical purposes, a need for 100 % predictable backup capacity prevailed. This insight can also be found in all the reports of the German transmission system operators on the energy performance of 2012 to 2016, which at the time of the annual peak load in Germany assume an unchanged non-availability of 99 % for the German wind fleet, despite significant additions to the fleet [24].

Furthermore, the energy performance report for 2015 of the German transmission system operators contains additional statements to the effect that, because of the simultaneity, for the demand (load) in the countries of Europe there demonstrably is no certainty of a positive cross-border compensating effect at the most critical time of

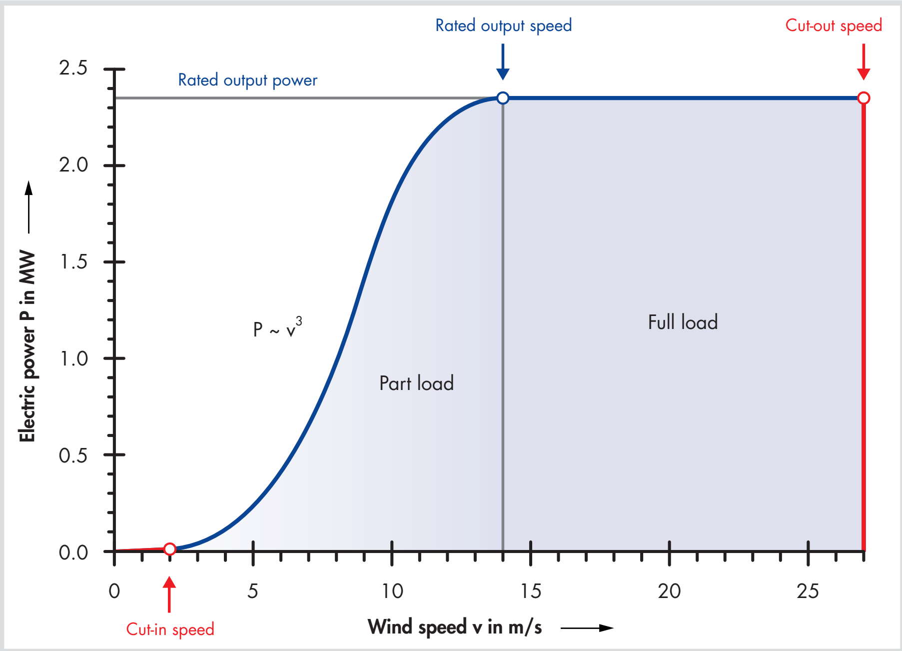

Fig. 5. Typical power curve of a modern wind turbine.

the year. The power that can be transferred between single countries is not arbitrarily high, the report states, and is reduced at some borders with increasing load or high wind power feed-in.

Considering the high level of expansion already achieved today, wind power alone is not suitable for reliable baseload application in Germany and is always dependent on complementary technologies that must be able to step into the breach at short notice as backup (rapid relief function).

One technical reason for the low level of the annual minimum values for electric power output, unchanged for years, could be the low-load capability of today's wind turbines, which are designed for maximum energy yield (Figure 5): Their rotors do not gather speed until wind speeds reach approximately 2 to 4 m/s (cut-in speed).

The power output at low wind speeds is, moreover, not proportional to the nominal power. In the part load range the power output of a modern wind turbine increases almost in proportion to the cube (the third power) of the wind speed. If the wind speed doubles, the power output increases by a factor of eight, and if the wind speed is halved, power output drops to an eighth of what it was before. When the nominal wind speed is reached and exceeded, the plant then continues to deliver its nominal power at a constant level until the cut-out speed is reached.

Apart from this technical cause of low levels of minimum values, energy meteorology aspects probably also play a role. Energy meteorology is devoted among other things to the description and modelling of the spatiotemporal characteristics and statistical distribution of wind fields. Bearing this in mind, statistical observations might also provide an explanation for the minimum values: A look at the frequency distribution and probability density function of the power output of the German wind fleet in 2016 (Figure 6) proves that there is no normal distribution and that low power outputs evidently occur much more frequently than high power outputs.

In statistical evaluations of random variables (here quarter-hour power output figures) the arithmetic mean μ (expected value) and the standard deviation σ as equivalent of the width of the frequency distribution of the observed random numbers play a role.

Based on the time series of electric power output of the German wind fleet in 2016 (quarter-hourly resolution) an arithmetic mean of 8,769 MW and a standard deviation of 6,852 MW can be derived. According to the frequency distribution of this power output (Figure 6) cumulative probabilities of occurrence of 60 % for power outputs below the mean can be derived, and 40 % for power outputs above the mean. Furthermore, the cumulative probability of power outputs in the range from 0 to about 2,000 MW, corresponding to a deviation by one standard deviation downwards from the mean (μ – σ), or less, amounts to around 10 % of all quarter-hourly values of the year 2016. This is equivalent to a cumulative duration of about 37 days.

In summary, therefore, it can be said: Electric power outputs near zero already are reached at small deviations of the arithmetic mean downwards from one standard deviation, and on average – in terms of cumulative duration in days – can be expected three times a month.

In Figure 7 the annual arithmetic means for the electric power output of the German wind fleet from 2010 to 2016 are plotted, in each case including one standard deviation from the arithmetic mean upwards and downwards in order to elucidate the statements made above.

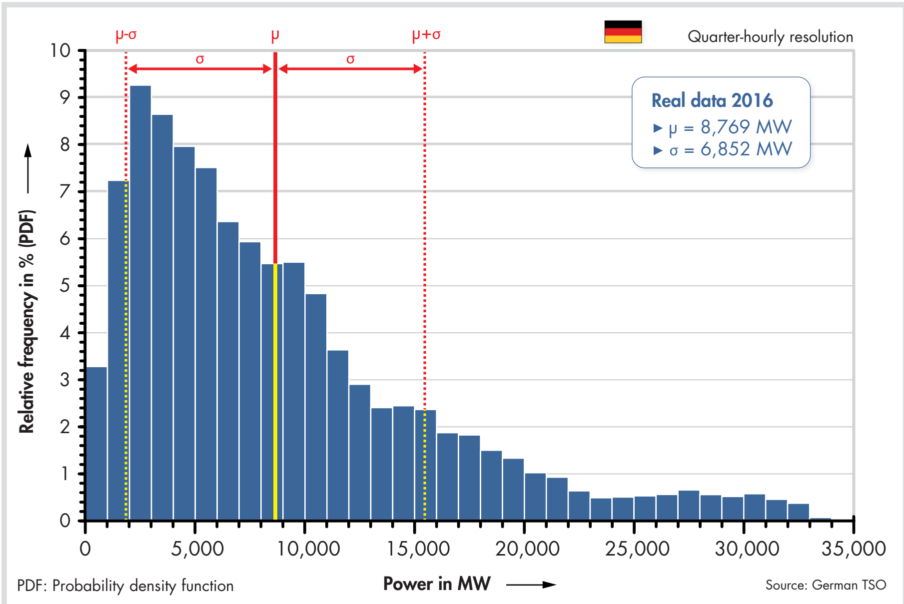

Fig. 6. Frequency distribution of electric power output of the German wind fleet in 2016.

In addition, along with a representative curve of the normal distribution, Figure 7 shows the curve of the frequency distribution of the wind fleet power output, derived from the real data. This figure provides evidence of the relatively high probability of annual minimum power output values near zero: The arithmetic mean and the standard deviation are about equally large in all years so that the relation of standard deviation to mean value, termed variation coefficient (a dimensionless equivalent of the degree of variation), always takes on values near one.

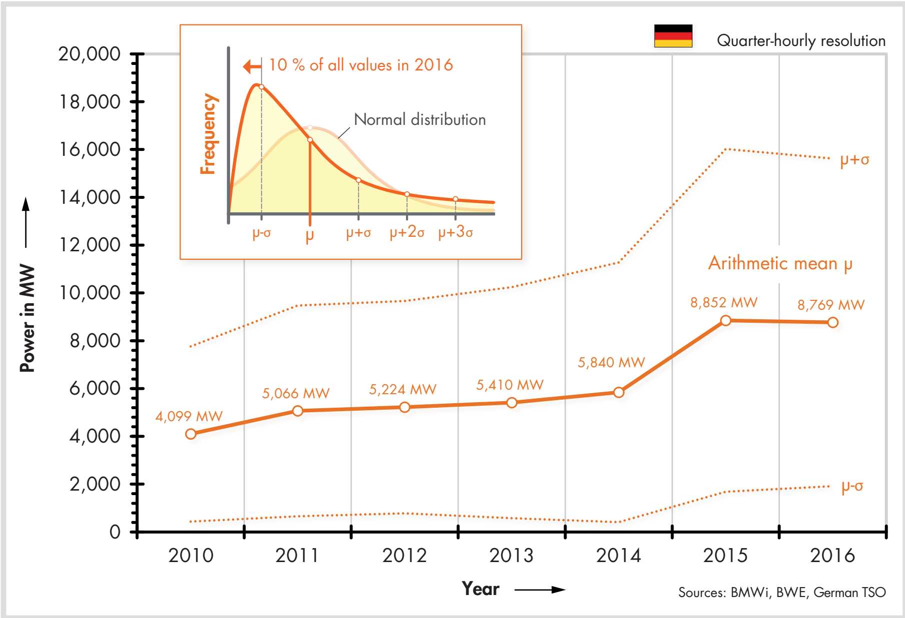

Fig. 7. Arithmetic mean of German wind fleet electric power output from 2010 to 2016 including one upward and one downward standard deviation from the mean for each year, respectively.

captive generation, from industry-owned combined heat and power plants (CHP), from small CHP units and from small-scale plants using renewables (private use), which are not recorded by transmission system operators in Germany, have to be deducted (together about 62 TWh), so that a total electricity consumption of 488 TWh results. This figure deviates by merely 2 % from the integral of the ENTSO-E time series. This deviation can be explained with uncertainties of data collection; the magnitude of the load thus appears plausible.

In December 2016 two weak wind phases with average wind fleet power outputs of less than about 5,000 MW occurred: One from 3 to 6 December 2016 (four days) and one from 12 to 20 December 2016 (nine days). In the night of 18 to 19 December the total electric power output of the wind fleet fell to a minimal value of 0.8 % of the nominal capacity. This confirms the current approach of the German transmission system operators, which assumes a 99 % non-availability of the wind fleet in annual

Detailed analyses of the frequency of weak wind phases in the period evaluated in this study prove that since 2010 around 160 five-day phases with average wind fleet power outputs of less than 5,000 MW have occurred in Germany. Furthermore, in every year since 2010 there were continuous ten- to 14-day weak wind phases.

Consequently, with average daily electricity requirements of 1.5 TWh in Germany, without today's conventional power plant fleet backup systems able to draw at any time on a working volume of 10 to 15 TWh and an average output of up to 50,000 MW (fluctuation range from 30,000 to 70,000 MW) would have to be maintained.

Moreover, three- to four-week weak wind phases with average wind fleet outputs below the 5,000 MW mark have occurred regularly in Germany, for example in June 2010, November 2011, August 2012, July 2014 and June 2016.

Considering these not uncommon wind conditions, on demand the backup system would even have to be able to reliably provide working volumes of 30 to 40 TWh and a power output averaging up to about 50,000 MW.

As final example for Germany, the month of December 2016 is cited, in which the wind fleet had a nominal capacity of around 50,000 MW (Figure 8), while the consumer load varied according to the time of the day and week within a range of roughly 40,000 to a little more than 70,000 MW.

From the time series of 2016 (hourly resolution) for the load P_L in Germany, an average value of 54,769 MW and a total annual energy of 481 TWh follow.

According to the definition of the Association of European Transmission System Operators ENTSO-E, this load can be computed starting from gross electricity generation by successively deducting the power plant auxiliary electric load, the balance of electricity imports and electricity exports and the power required for the pump mode of pumped storage power plants (pumping energy).

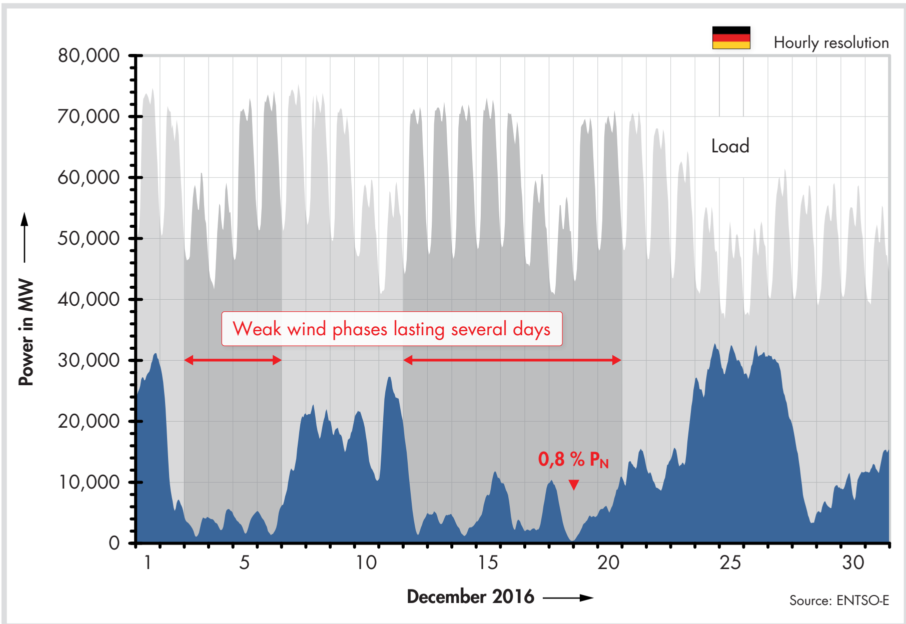

Fig. 8. Consumer load and electricity generation from wind power in Germany in December 2016.

From statistical 2016 data for Germany, applying the aforesaid calculation rule one gets the following result: Starting from last year's gross electricity generation (about 648 TWh) the auxiliary electric load of the power plants (36 TWh), the import-export balance (54 TWh) and the pumping energy (8 TWh) must be deducted. From the resulting total electricity consumption (550 TWh), which still includes grid losses, contributions from the German railways' peak load analyses in the spirit of the criteria supply security and grid stability.

In the first weak wind phase, for four days an average power output of 3,347 MW, which, added up, gave an electric energy of 0.3 TWh, was available from wind power, while the residual load – the difference between demand and electricity generation from wind power – averaged 54,763 MW, corresponding to an electric energy of 5.3 TWh.

In the second weak wind phase, for nine days wind energy delivered an electric power output averaging 5,126 MW corresponding to an electric energy of 1.1 TWh. The residual load during this period averaged 54,713 MW, corresponding to an electric energy of 11.8 TWh.

This example shows that the challenges presented by the "Energiewende" with the envisaged increased future expansion of intermittent renewable energy systems (iRES) are large, especially during winter months, when contributions from photovoltaics are small to extremely small (in the late afternoon).

In cases in which wind energy and photovoltaics simultaneously fail ("dark doldrums"), other power plant systems must step into the breach as backup and be 100 % available.

Summary and outlook

Given the current energy policy and regulatory environment, which in view of Germany's international climate protection obligations aims at the abandonment of well-established power plant technology that has worked effectively for many decades and at the provision of electric energy mostly from renewables, for all practical purposes only solar energy (photovoltaics) and wind power remain open to further development as silver bullet technologies for the "Energiewende".

The results of the evaluations and analyses of the development and operating characteristics of the German wind fleet from 2010 to 2016 show that the nominal capacity of the German wind fleet doubled to around 50,000 MW in the period concerned. The annual electricity production from wind power increased over the same period to 77 TWh and has thus even more than doubled.

Despite these additions to the wind fleet throughout Germany, and contrary to the intuitive assumption that a wide-ranging distribution of locations for wind power should lead to balancing or smoothing of the aggregate electric power output from all wind turbines, since the year 2010 no increase can be detected in the annual minimum values (power feed-in data recorded on a quarter-hourly to hourly base). 2016 as well saw unchanged values of less than 150 MW or 1 % of the cumulative nominal power of the German wind fleet.

From the viewpoint of security of supply, so far wind power in Germany has replaced conventional power plant output of no more than 150 MW. For comparison: In terms of the stability of the electricity grid in Germany, a power plant capacity of about 77,000 to 82,000 MW is required at the time of the annual peak load, which can occur usually on a late afternoon on a day in the period from November to February and is not known in advance.

The continuously available and therefore secured electric power output of the German wind fleet thus always was significantly less than one percent of its nominal capacity, or, in other words: In every year there was always at least one quarter of an hour in which more than 99 % of the nominal capacity of the German wind fleet was not available and, for all practical purposes, a need for 100 % predictable backup capacity prevailed. These statements also apply to offshore wind energy.

For these low minimum values, unchanged for years, intrinsic low energy density of wind and technical reasons – the low-load capability of wind turbines, which to date are designed for maximum energy yield (EEG subsidies) – can be cited. In addition, meteorological aspects and the large spatiotemporal variation of wind energy due to wind speed fluctuations play a role. Electricity generation from wind power is determined by weather conditions with typical correlation lengths of several hundred kilometres. The resulting aggregate electric power output for Germany is highly volatile and on top of that is not normally distributed. The variation coefficients of the analysed seven time series of electric power output of the German wind fleet from 2010 to 2016, which all reach values near one and are an indication of high volatility and a high degree of variation, also show that there is a high probability of low aggregate power outputs.

Accompanying analyses of the frequency of weak wind phases from 2010 to 2015 show that a total of about 160 five-day phases with average wind fleet electric power outputs of less than about 5,000 MW occurred in this period and that there were continuous ten- to 14-day weak wind phases in every year. With daily electricity requirements averaging 1.5 TWh in Germany, without conventional power plants, backup systems would need to be provided that have an always available working volume in the mid-double-digit TWh range.

In the second part of the study, in the light of the knowledge obtained so far emphasis will be on the question whether adequate possibilities for mutual balancing exist within the interconnected European grid, true to the motto "the wind is always blowing somewhere".

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