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Chapter 8 in Wind Power in Power Systems.
Ed. by Ackermann, T. John Wiley & Sons Ltd,
2005. Pp. 144–167. (In print.) ISBN 0-470-85508-8 (HB)

Power System Requirements for Wind Power

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8.1 Introduction

The power system requirements for wind power mainly depend on the power system configuration, the installed wind power capacity, and how the wind power production varies. Wind resources vary on every time scale: seconds, minutes, hours, days, months and years. On all these time scales, the varying wind resources affect the power system. An analysis of this impact will be based on the geographical area that is of interest. The relevant wind power production to analyse is that of larger areas, like synchronously operated power systems, comprising several countries or states.

The integration of wind power into regional power systems is mainly studied on a theoretical level, as wind power penetration is still rather limited. Even though the average annual wind power penetration in some island systems (e.g. Crete in Greece)[1] or countries (e.g. Denmark)[2] is already high, on average wind power generation represents only 1–2 % of the total power generation in the Scandinavian power system (Nordel) or the Central European system (UCTE). And the penetration levels in the USA (NERC regions) are even lower. Most examples in this chapter come from Central and Northern Europe, as there is already some experience with large-scale integration of wind power, and there are far-reaching targets for wind power. In Central Europe, power production is mostly based on thermal production, whereas in the Nordic countries thermal production is mixed with a large share of hydro power.

We will refer to the energy penetration when we use the term wind power penetration in the system. The energy penetration is the energy produced by wind power (annually) as a percentage of the gross electricity consumption. Low penetration means that less than 5 % of gross demand is covered by wind power production, high penetration is more than 10 %. First, this chapter will describe the power system and large-scale wind power production. We will then look at the effects of wind power production on power system operation as well as present results from studies in order to quantify these effects.

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[1] See also chapter 14.
[2] See also chapter 3, 10 and 11.

8.2 Operation of the Power System

Electric power systems include power plants, consumers of electric energy and transmission and distribution networks connecting the production and consumption sites. This interconnected system experiences a continuous change in demand and the challenge is to maintain at all times a balance between production and consumption of electric energy. In addition, faults and disturbances should be cleared with the minimum effect possible on the delivery of electric energy.

Power systems comprise a wide variety of generating plant types, which have different capital and operating costs. When operating a power system, the total amount of electricity that is provided has to correspond, at each instant, to a varying load from the electricity consumers. To achieve this in a cost-effective way, the power plants are usually scheduled according to marginal operation costs, also known as merit order. Units with low marginal operation costs will operate almost all the time (base load demand), and the power plants with higher marginal operation costs will be scheduled for additional operation during times with higher demand. Wind power plants as well as other variable sources, like solar and tidal, have very low operating costs. They are usually assumed to be 0, therefore these power plants are at the top of the merit order. That means that their power is used whenever it is available. The electricity markets operate in a similar way, at least in theory. The price the producers bid to the market is slightly higher than their marginal cost, because it is cost-effective for the producers to operate as long as they get a price higher than their marginal costs. Once the market is cleared, the power plants that operate at the lowest bids come first.

If the electricity system fails the consequences are far-reaching and costly. Therefore, power system reliability has to be kept at a very high level. Security of supply has to be maintained both short-term and long-term. This means maintaining both flexibility and reserves that are necessary to keep the system operating under a range of conditions, also in peak load situations. These conditions include power plant outages as well as predictable or uncertain variations in demand and in primary generation resources, including wind.

The power system has to operate properly also in liberalised electricity markets. Usually, an Independent System Operator (ISO) is the system responsible grid company that takes care of the whole system operation, using active and reactive power reserves to maintain system reliability, voltage and frequency.

Reliability consists of system security and adequacy. The system security defines the ability of the system to withstand disturbances. The system adequacy describes the amount of production and transmission capacity in varying load situations.

8.2.1 System reliability

The planning of the power system is usually carried out according to mutually agreed principles. These principles include that the system has to withstand any single fault (e.g. the disconnection of a power plant, transmission line, substation busbar or power transformer) without major interruptions of the power delivery. The consequences of faults for the power system depend on the power transmission (i.e. the production and consumption of electric energy at a given moment), on the topology of the system and on the type of the fault. The most severe fault that a power system can withstand and that will not lead to inadmissible consequences is called dimensioning fault. The dimensioning fault varies according to the operational state of the system. Usually, it is the disconnection of the largest production unit or the busbar fault at a substation residing along an important transmission route.

Limits for power transfers are defined in predefined production and loading situations using power system analysis software, where the equipment (lines, substations, power plants and loads) is modelled together with connections and levels of production and load. In the simulations, the dimensioning fault(s) may not lead to situations, where synchronous operation is lost, or there may be voltage collapses, load shedding, large deviations in voltage/frequency, overloads or un-damped oscillations. The normal operational state of the power system is a power transfer state, where the system can withstand a dimensioning fault without the resulting disturbance spreading further than allowed. Within a normal operation area that consists of normal power transfer states, the faulty equipment can be disconnected in case of a fault. Disturbances are not allowed to spread to a larger area or cause a blackout of the system.

The system responsible ISO provides disturbance management that prevents faults from spreading and restores the system to normal operational state as soon as possible after the fault. The security of the power system is maintained by planning and operating the system in a way that minimises disturbances caused by faults. In order to manage disturbances, the system responsible grid operator keeps power transfers within the allowed limits and secures that the system has enough reserves in power plants and in the transmission grid.

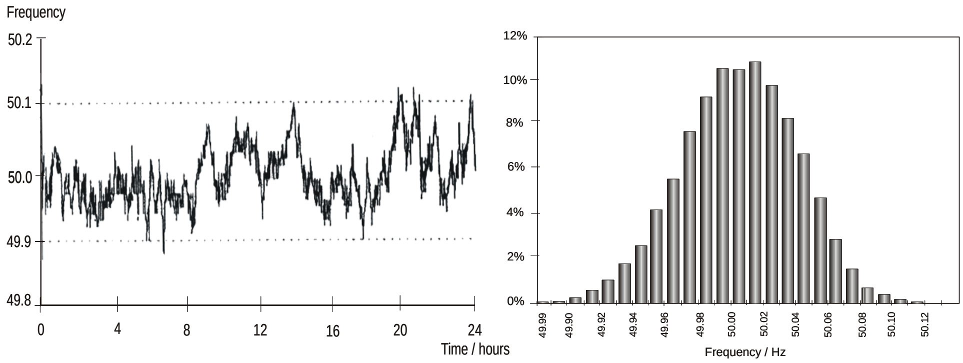
System adequacy is associated with static conditions of the system. It refers to the existence of sufficient electric energy production within the system to meet the load demand or constraints within the transmission and distribution system. The adequacy of the system is usually studied either by a simple generation–load model or by an extended bulk transmission system model consisting of generation, transmission, distribution and load. In a simple generation–load model, the total system production is examined to define its adequacy to meet the total system load. The estimation of the required production needs includes the system load demand and the maintenance needs of production units. The criteria that are used for the adequacy evaluation include the loss of load expectation (LOLE), the loss of load probability (LOLP) and the loss of energy expectation (LOEE), for instance.

The LOLP approach combines the applicable system capacity outage probability with the system load characteristics in order to arrive at the expected probability of loss of load. LOLE defines the number of days or hours per year with a probability of loss of load. LOEE defines the same values for energy (Billinton and Allan, 1988).

8.2.2 Frequency control

The power system that is operated synchronously has the same frequency. The frequency of a power system can be considered a measure of the balance or imbalance between production and consumption in the power system. With nominal frequency (e.g. in Europe 50 Hz, in the US 60 Hz), production and consumption, including losses in transmission and distribution, are in balance. If the frequency is below 50 Hz, the consumption of electric energy is higher than the production. If the frequency is above 50 Hz, the consumption of electric energy is lower than the production. The better the balance between production and consumption, the less the frequency deviates from its nominal value. In the Nordic Power System, for instance, the frequency is allowed to vary between 49.9 Hz and 50.1 Hz. Figure 8.1a shows an example of frequency variations during one day and figure 8.1b presents frequency variations during one week.

The primary frequency control in power plants is used to keep the frequency of the system within the allowed limits. The primary control is activated automatically if the frequency fluctuates. It is supposed to be fully activated when the maximum allowable frequency deviation (e.g. in Nordic Power System ± 0.1 Hz) is reached. Figure 8.2 shows an example of the actual load in the system during 3 hours compared to the hourly load forecast, including forecast errors and short-term load deviations in the system.



a) b)

Figure 8.1 Examples of: a) frequency variations in the system during one day; b) frequency distribution in the system during one week (Source: Hirvonen, 2000).

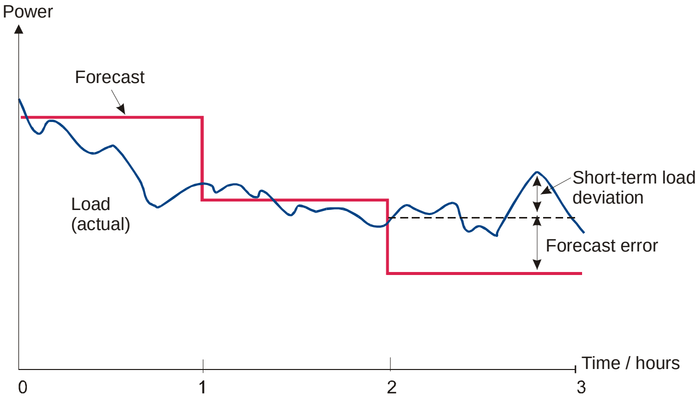


Figure 8.2 Example of actual load in the system during 3 hours compared to forecasted load. (Source: Holttinen, 2003)

If there is a sudden disturbance in balance between production and consumption in the power system, such as the loss of a power plant or a large load, primary reserves (also called disturbance reserve or instantaneous reserve) are used to deal with this problem. The primary reserve consists of active and reactive power supplied to the system. Figure 8.3 shows the activation of reserves and frequency of the system as a function of time, for a situation where a large power plant is disconnected from the power system. Their activation time divides the reserves into primary reserve, secondary reserve (also called fast reserve) and long-term reserve (also called slow reserve or tertiary reserve), as shown in figure 8.3.

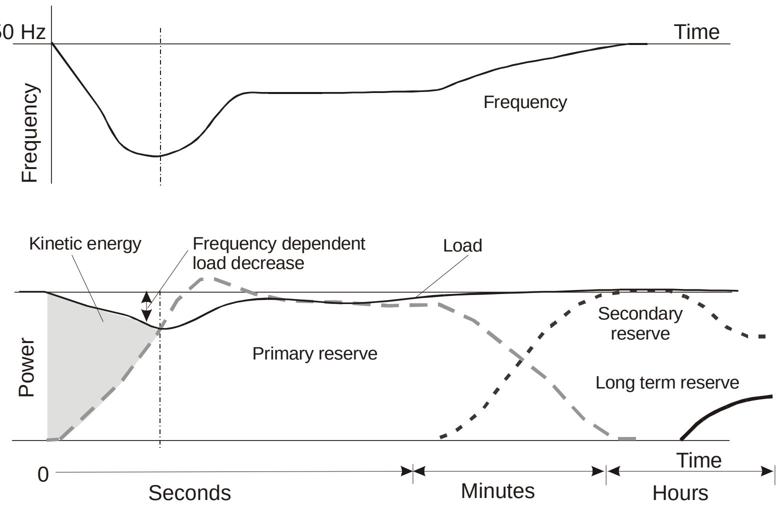


Figure 8.3 Activation of power reserves and frequency of power system as a function of time, for a situation where a large power plant is disconnected from the power system. (Source: Hirvonen, 2000).

The primary reserve is production capacity that is automatically activated within 30 seconds from a sudden change in frequency. It consists of active and reactive power in power plants, on the one hand, and loads that can be shed in the industry, on the other hand. Usually, the amount of reserve in a system is defined according to the largest power plant of the system, which can be lost in a single fault.

The secondary reserve is active or reactive power capacity activated in 10 to 15 minutes after the frequency has deviated from the nominal frequency. It replaces the primary reserve and it will be in operation until long-term reserves replace it, as shown in figure 8.3. The secondary reserve consists mostly of rapidly starting gas turbine power plants, hydro (pump) storage plants and load shedding. Every country in an interconnected power system should have a secondary reserve. It corresponds to the amount of disconnected power during the dimensioning fault (usually loss of largest power unit) in the country involved. In order to provide sufficient secondary power reserve, system operators may take load-forecast errors into account. In this case, the total amount of the secondary reserve may reach a value corresponding to about 1.5 times the largest power unit.

8.2.3 Voltage management

The voltage level in the transmission system is kept at a technical and economical optimum by adjusting the reactive power supplied or consumed. Power plants and special equipment, e.g. capacitors and reactors, control the reactive power. The voltage ratio of different voltage levels can be adjusted by tap-changers in power transformers. This requires a reactive power flow between different voltage levels.

In order to manage the voltage level during disturbances, reactive reserves in power plants are allocated to the system. These reserves are mainly used as primary reserves in order to guarantee that the voltage level of the power system remains stable during disturbances.

The voltage level management has the aim to prevent under- and over-voltages in the power system and to minimise grid losses. Voltage level management also guarantees that customer connection points have the voltages that were agreed by contracts.

8.3 Wind Power Production and the Power System

Wind energy is characterised by large variations in the production. If we look at the power system, we are interested in the wind power production of larger areas. Large geographical spreading of wind power will reduce variability, increase predictability and there will be less instances of near zero or peak output.

For power systems, the relevant information on wind power production is the probability distribution, the range and seasonal or diurnal patterns of the production, as well as the magnitude and the frequency of the variations (ramp rates).

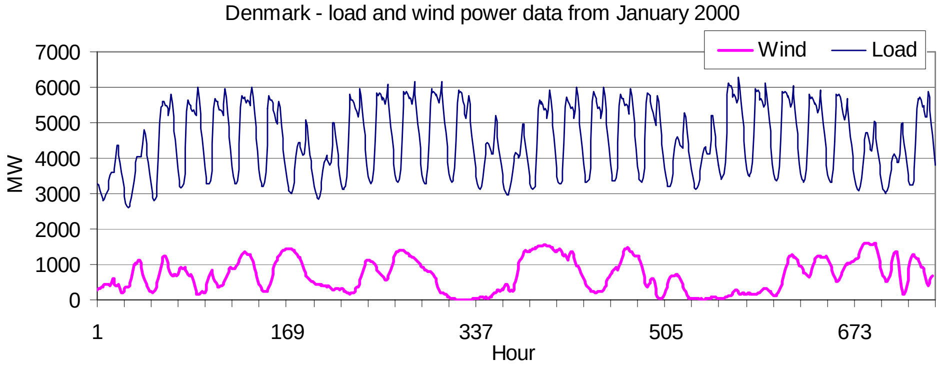


Figure 8.4 Example of large-scale wind power production: Denmark (both Zeeland and Jutland) in January 2000. Average wind power production in January was 687 MW and in 2000 all year 485 MW (~24 % of the installed capacity). (Source: Holttinen, 2003)

8.3.1 Production patterns of wind power

Wind power production is highly dependent on the wind resources at the site. Therefore the average production, the distribution of the production, as well as seasonal and diurnal variations can look very different at different sites and areas of the world. For most sites on land, the average power as the percentage of the nominal capacity (capacity factor c_p), is between 20–40 %. This can be expressed as full load hours of 1,800–3,500 h/a. Full load hours are the annual production divided by the nominal capacity. Offshore wind power production, or some extremely good sites on land, can reach up to 4,000–5,000 full load hours (c_p 45–60 %).

We can compare that to other forms of power generation. Combined heat and power production (CHP) has full load hours in the range of between 4,000–5,000 h/a, nuclear power 7,000–8,000 h/a, and coal fired power plants 5,000–6,000 h/a. However, full load hours are only used to compare different power plants. They do not tell us how many hours the power plant is actually in operation. Wind turbines, which operate most of the time at less than half of the nominal capacity, will typically produce power during 6,000–8,000 h/a (70–90% of the time).

The geographical spreading of the production evens out the variations of the total production from an area. There will be substantially less calm periods, as the wind will blow almost always somewhere in the area that the power system covers. On the other hand, maximum production levels will not reach the installed nominal capacity, as the wind will not have the same strength at all sites simultaneously. And out of hundreds or thousands of wind turbines not all will be technically available in each and every moment.

The duration curve of dispersed wind power production in figure 8.5 illustrates that: the production from one wind turbine is zero for 10–20 % of the time, and at nominal capacity 1–5 % of the time, whereas the production from large-scale wind power production is in this example rarely below 5 % or above 75 % of capacity.

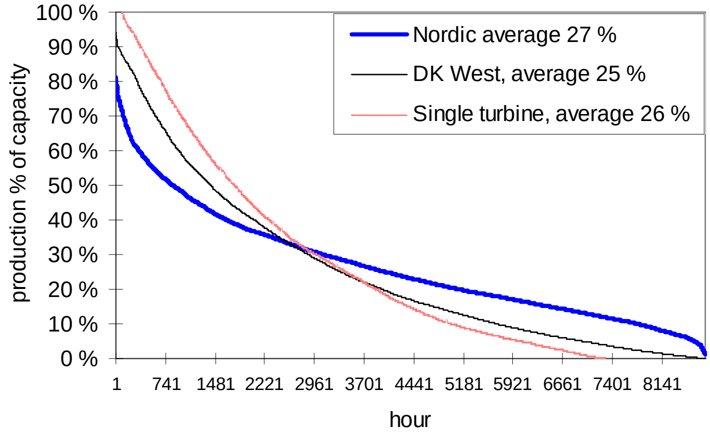


Figure 8.5 Increased resources and geographical spreading lead to a flattened duration curve of wind power production. Example of year 2000 hourly data, where wind power production from turbines throughout the four Nordic countries, Denmark, Finland, Norway and Sweden, is compared with one of the wind farms and one of the areas (Denmark, West). (Source: Holttinen, 2003)

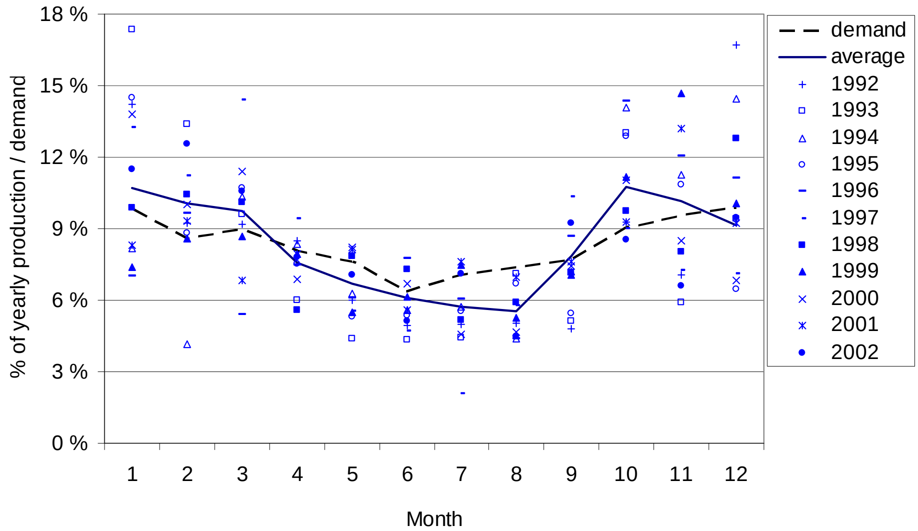


Figure 8.6 Seasonal variations of wind power production. Example from Finland for the years 1992–2002. Average monthly production in 1992–2002 is shown (solid line) together with the electric consumption in 2002 (dotted line). (Source: Holttinen, 2003)

Even for large-scale, geographically dispersed wind power production, the production range will still be large compared with other production forms. The maximum production will be three or even four times the average production, depending on the area (Holttinen, 2003, Giebel 2000).

The available wind resources will vary from year to year. Wind power production during one year lies at between ± 15 % of the average long-term yearly production (Ensslin et al, 2000; Giebel, 2001). However, the year-to-year variation in the production from hydro power can be even larger.

There is often a distinct yearly (seasonal) and daily (diurnal) pattern in wind power production. In Central and Northern Europe, there is more production in winter than in summer (Fig. 8.6).

Wind is driven by weather fronts. It may also follow a daily pattern caused by the sun. Depending on what is prevalent in the region, there is either a strong or hardly any diurnal pattern in the production. There are many sites where the wind often starts to blow in the morning and calms down in the evening (Hurley and Watson, 2002; Ensslin et al, 2000). In Northern Europe, this is most pronounced during the summer (see Figure 8.7). Diurnal variation can also be due to local phenomena. An example would be the mountain ranges in California with morning and evening peaks, when wind blows from the desert to the sea and in the opposite direction, respectively.

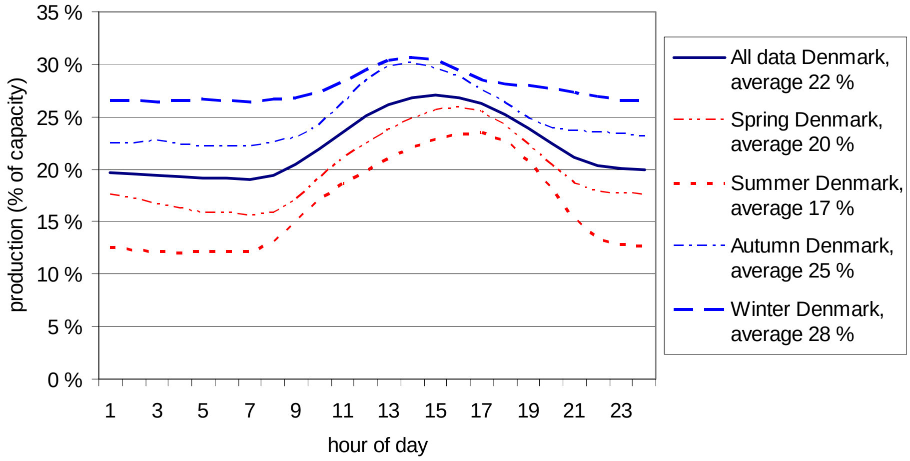


Figure 8.7 Diurnal variations of wind power production are larger during the summer, example from Denmark.

8.3.2 *Variations of production and smoothing effect*

The wind speed varies on all time scales, and this has different effects on the power system. Wind gusts cause variations in the range of seconds or minutes. The changing weather patterns can be seen from the hourly time series of wind power production. This time scale also illustrates the diurnal cycle. Seasonal cycles and annual variations, on the other hand, are important for long-term adequacy studies. For the system planning, it is important to look at extreme variations of large-scale wind power production, together with the probability of such variations.

The larger the area, the longer the periods of time over which the smoothing effect extends. Figure 8.8 shows the decreasing correlation[3] of the variations for different time scales (Ernst, 1999). The correlation is here calculated for the differences between consecutive production values (ΔP). For the time series of production values, the correlation does not decrease as rapidly as shown here. Within one wind farm, gusts (seconds) will not effect all wind turbines at exactly the same moment. However, the hourly wind power production will follow approximately the same ups and downs. In a larger area covering several hundreds of square kilometres, the weather fronts causing high winds will not pass simultaneously over the entire regions. However, high and low wind months will coincide for the whole area.

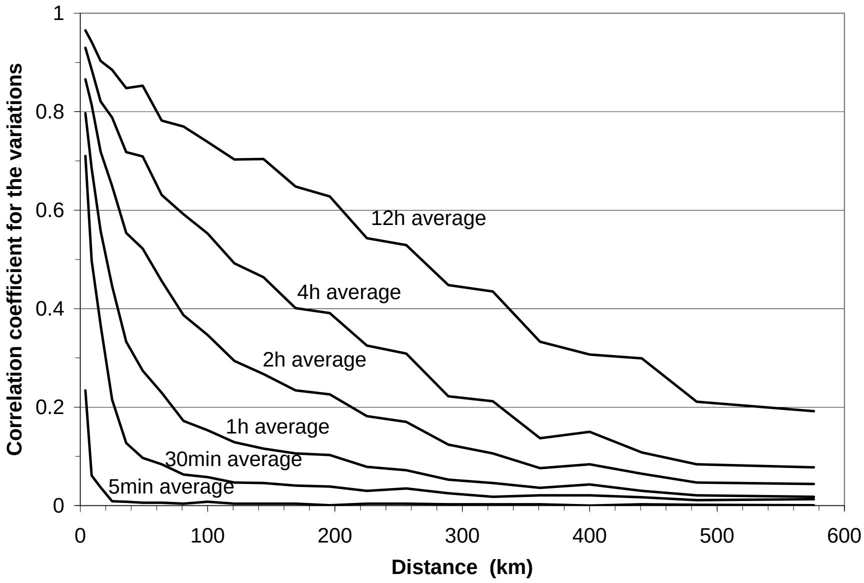


Figure 8.8 Variations will smooth out faster when the time scale is small. Correlation of variations for different time scales, example from Germany (Ernst, 1999).

How large is the smoothing effect? It becomes more noticeable if there is a larger number of turbines spread over a larger area. The smoothing effect of a specified area has an upper limit. There will be a saturation of the amount of variations, i.e. where an increase in the number of turbines will not decrease the (relative) variations by the total wind power production of the area. Beyond that point, the smoothing effect can be only increased when the area becomes larger. And there is a limit to that, too. The examples we use are from comparatively uniform areas. If wind power production is spread over areas with different weather patterns (coast/mountains/desert), the smoothing effect will probably be stronger.

[3] Cross-correlation r_{xy} is a measure of how well two time series follow each other: it is near the maximum value 1 if the ups and downs of the production occur simultaneously, near the minimum value –1 if there is a tendency of decreasing production at one site while increasing production at the other site, and it is close to zero if the two are uncorrelated, and the ups and downs of production at two sites do not follow each other.

$$r_{x,y} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\mu_x)(y_i-\mu_y)}{\sigma_x\sigma_y}$$, where μ denotes the average, σ the standard deviation and n the number of points in the time series.

The smoothing effect is illustrated by the statistical parameters of the production (P) and fluctuation (ΔP) time series, i.e. the maximum variations of production (extreme ramp rates), the probability distribution of the variations and the standard deviation (σ).

The second-to-second variations will be smoothed out already for one wind turbine. The inertia of the large rotating blades of a variable speed wind turbine smoothes out very fast gusts. Second-to-second variations will be absorbed in the varying speed of the rotor of a variable speed wind turbine. The extreme ramp rates that were recorded for a 103 MW wind farm are: 4…7 % of capacity in a second, 10…14 % of capacity in a minute and 50…60 % of capacity in an hour (Parsons et al, 2001). However, system operation is concerned with an area that is much larger than the area in this example. For a larger area with geographically dispersed wind farms, the second and minute variations will not be significant, and the hourly variations will be considerably less than 50–60 % of capacity.

The largest hourly variations are about ± 30 % of capacity when the area is in the order of 200x200 km^2 (such as West/East Denmark), about ± 20 % of capacity when the area is in the order of 400x400 km^2 (such as Germany; Denmark; Finland; Iowa, US) and about ± 10 % in larger areas covering several countries, e.g. the Nordic countries (ISET, 2002; Holttinen, 2003; Milligan & Factor, 2000). These are extreme values. Most of the time the hourly variations will be within ± 5 % of installed capacity (Fig. 8.9).

If the geographic dispersion of wind power increases, the standard deviation for hourly time series decreases, which means that the variability in the time series is reduced. The standard deviation of hourly time series decreases to 50–80 % of the single site value (Focken et al, 2001; Holttinen, 2003). The standard deviation of the time series of fluctuations ΔP will decrease even faster, from about 10 % of capacity for a single turbine to less than 3 % for an area like Denmark or Finland and to less than 2 % for the 4 Nordic countries (Milborrow, 2001; Holttinen, 2003).

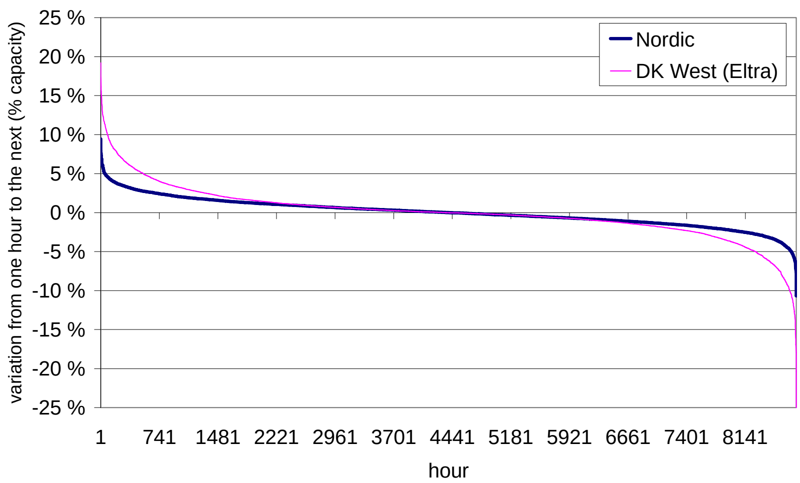


Figure 8.9. Variation of wind power production from one hour to the next. Duration curve of variations, as a percentage of installed capacity, for Denmark (Jutland) and for the theoretical Nordic wind power production assuming equal production in each of the four countries, year 2000. (Source: Holttinen, 2003)

According to (ISET, 2002), in Germany, maximum variation for 4 hours ahead is 50 % of capacity and for 12 hours ahead is 85 % of capacity. If we take larger areas, such as Northern Europe, there is a ± 30 % variation in production 12 hours ahead only about once a year (Giebel, 2000). For longer time scales (i.e. 4–12 h variations), prediction tools give valuable information on the foreseeable variations of wind power production.

Diurnal variations in output can help to indicate at what time of the day significant changes in output are most likely to occur. The probability of significant variations is also a function of the output level. Significant variations are most likely to occur when wind farms operate at between 25–75 % of capacity. This output level corresponds to the steep part of the power curve when changes in wind speed produce the largest changes in power output of the turbines (Poore & Randall, 2001).

There are also means to reduce the variations of the wind power production. Staggered starts and stops from full power as well as reduced (positive) ramp rates can reduce the most extreme fluctuations, in magnitude and frequency, over the short time scales. However, this is at the expense of production losses. Therefore, the frequent use of these options should be weighed against other measures (in other production units), regarding their cost effectiveness.

8.3.3 Predictability of wind power production

Wind power prediction plays an important part in the system integration of large-scale wind power. If the share of installed wind power is substantial, information regarding the on-line production and predictions of 1 to 24 h ahead are necessary. Day-ahead predictions are required in order to schedule conventional units. The starting up and shutting down of slow starting units has to be planned in an optimised way in order to keep the units running at the highest efficiency possible and to save fuel and thus operational costs of the power plants. In liberalised electricity markets, this is dealt with at the day-ahead spot market. Predictions of 1–2 h ahead help to keep up the optimal amount of regulating capacity at the system operators' disposal.

Predictability is most important both at times of high wind power production and for a time horizon of up to 6 hours ahead, which gives enough time to react on varying production. An estimate of the uncertainty, especially the worst-case error, is important information.

Forecast tools for wind power production are still under development and they will be improving.[4] The predictions of the power production 8 hours ahead or more rely almost entirely on meteorological forecasts for local wind speeds. In northern European latitudes, for example, the variations of wind power production correspond to weather systems passing the area, causing high winds, which then calm down again. The wind speed forecasts of the Numerical Weather Prediction models contribute the largest error component. So far, an accuracy of ± 2–3 m/s (level error) and ± 3–4 h (phase error) has been sufficient for wind speed forecasts. However, the power system requires a more precise knowledge of the wind power production[5].

For larger areas, the prediction error decreases. For East and West Denmark, for example, including East Denmark adds 100 km, or 50 % more to West Denmark's area, in the direction in which most weather systems pass. The errors of day-ahead predictions would cancel out each other to some extent for about a third of the time, when production is overpredicted in the West and underpredicted in the East, or vice versa (Holttinen, 2004).

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[4] See also Chapter 17.

[5] See also Chapters 10.

8.4 Effects of Wind Energy on the Power System

The impact of wind power on the power system depends on the size and inherent flexibility of the power system. It is also related to the penetration level of wind power in the power system.

When studying the impact of wind power on power systems, we refer to an area that is larger than only one wind farm. According to the impact that is analysed, we have to look at the power system area that is relevant. For voltage management, only areas near wind power plants should be taken into account. Even though there should be enough reactive power reserve in the system during disturbances, the reserve should mainly be managed locally. For intra-hour variations, frequency control for load following, we should look at the area of the synchronously operated system. DC links connecting synchronously operated areas can also be automised to be used for primary power control[6]. However, their power reserve capacity is usually only allocated as emergency power supply. For the day-ahead hourly production, a relevant area would be the electricity market. The Nordic power market, for instance, includes countries that are situated in different synchronous systems. Large interconnected areas lead to substantial benefits, unless there are bottlenecks in transmission[7].

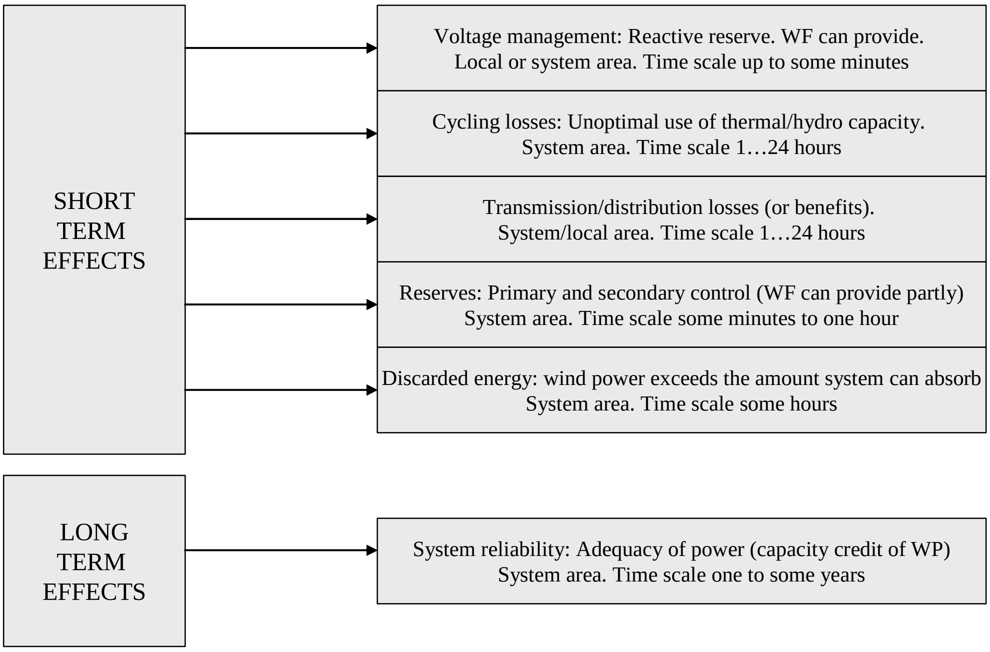

Figure 8.10 Power system impacts of wind power, causing integration costs. Some of the impacts can be beneficial for the system, and wind power can provide a value, not only costs (Source Holttinen, 2003).

If we analyse the incremental effects that a varying wind power production has on the power system, we have to study the power system as a whole. The power system serves all production units and loads. The system has only to balance the net imbalances.

Power system studies require representative wind power data. If the data from too few sites is up-scaled the power fluctuations will be up-scaled, too. If large-scale wind power production with steadier wind resources (e.g. offshore or large wind turbines with high

[6] See Chapter 10.
[7] See Chapter 20.

towers) is incorporated into the system, measurements from land or with too low masts will, in turn, over-estimate the variations. In addition, most studies will require several years of data.

Figure 8.10 includes a schematic representation of the impact that wind energy has on the system. These impacts can be categorised as follows:

- short-term: balancing the system on the operational time scale (minutes to hours)
- long-term: providing enough power during peak load situations.

These issues will be discussed in more detail in the following sections. For long-term trends affecting the integration of wind power into future power systems, see section 8.4.4.

8.4.1 Short-term effects on reserves

The additional requirements and costs of balancing the system on the operational time scale (from several minutes to several hours) are primarily due to the fluctuations in power output generated from wind. A part of the fluctuations is predictable for 2 h to 40 h ahead. The variable production pattern of wind power changes the scheduling of the other production plants and the use of the transmission capacity between regions. This will cause losses or benefits to the system due to the incorporation of wind power. Part of the fluctuations, however, is not predicted or wrongly predicted. This corresponds to the amount that reserves have to take care of.

The impact on reserves has to be studied on the basis of a control area. It is not necessary to compensate every change in the output of an individual wind farm by a change in another generating unit. The overall system reliability should remain the same, before and after the incorporation of wind power. The data used for wind power fluctuations is critical to the analysis. It is important not to up-scale the fluctuations when wind power production in the system is up-scaled. Any wind power production time series that is simulated or based on meteorological data should therefore follow the statistical characteristics that were presented in the section 8.3 (Milborrow, 2001; Holttinen, 2003).

The system needs power reserves for disturbances and for load following. Disturbance reserves are usually dimensioned according to the largest unit outage. As wind power consists of small units, there is no need to increase the amount of disturbance reserve (even large offshore wind farms still tend to be smaller than large condense plants). Hourly and less than hourly variations of wind power affect the reserves that are used for frequency control (load following), if the penetration of wind power is large enough to increase the total variations in the system.

Prediction tools for wind power production play an important role in the integration. The system operator has to increase the amount of reserves in the system because, in addition to load swings, it has to be prepared to compensate unpredicted variations in the production. The accuracy of the wind forecasts can contribute to risk reduction. An accurate forecast allows the system operator to count on wind capacity, thus reducing costs without jeopardising system reliability.

The requirement of extra reserves is quantified by looking at the variations of wind power production, hourly and intra-hour, together with load variations and prediction errors. Extra reserve requirement of wind power, and the costs associated with it, can be estimated either by system models or by analytical methods using time series of wind power production together with system variables. Wind power production is not straightforward to model in the existing dispatch models, because of the uncertainty of forecast errors involved on several time scales, for instance (Dragoon and Milligan, 2003). Below, we will briefly describe analytical methods with statistical measures.

The effect of the variations can be statistically estimated using standard deviation. What the system sees is net load (load minus wind power production). If load and wind power production are uncorrelated, the net load variation is a simple root-mean-square combination of the load and wind power variation:

$$(\sigma_{total})^2 = (\sigma_{load})^2 + (\sigma_{wind})^2 \quad (8.1)$$

The larger the area in question and the larger the inherent load fluctuation in the system, the larger the amount of wind power that can be incorporated into the system without increasing variations. The reserve requirement can be expressed as three times the standard deviation (3σ cover 99 % of the variations of a Gaussian distribution). The incremental increase from combining load variations with wind variations is 3 times ($\sigma_{total} - \sigma_{load}$). More elaborate methods allocating extra reserve requirements for wind power can be used, especially with non-zero correlations and any number of individual loads and/or resources (Kirby & Hirst, 2000; Hudson et al, 2001).

On the time scale of seconds/minutes (primary control) the estimates for increased reserve requirements have resulted in a very small impact (Ernst, 1999; Smith et al, 2004). This is due to the smoothing effect of very short variations of wind power production; as they are not correlated they cancel out each another, when the area is large enough.

For the time scale of 15 min…1 hour (secondary control) it should be taken into account that load variations are more predictable than wind power variations. For this, data for load and wind predictions are needed. Instead of using time series of load and wind power variations, the time series of prediction errors one hour ahead are used and standard deviations are calculated from these. The estimates for reserve requirements due to wind power have resulted in an increasing impact if penetration increases. For a 10 % penetration level, the extra reserve requirement is in the order of 2…8 % of the installed wind power capacity (Milborrow, 2001; Milligan, 2003; Holttinen, 2003).

Both the allocation and the use of reserves cause extra costs. Regulation is a capacity service and does not involve net energy, as the average of regulation time series is zero. In most cases, the increase in reserve requirements at a low wind power penetration can be handled by the existing capacity. This means that only the increased use of dedicated reserves, or increased part-load plant requirement, will cause extra costs (energy part). After a threshold, also the capacity cost of reserves has to be calculated. This threshold depends on the design of each power system. Estimates of this threshold suggest for Europe a wind power (energy) penetration of between 5 and 10 % (Milborrow, 2001; Persaud et al, 2000; Holttinen, 2003).

Estimates regarding the increase in secondary load following reserves in the UK's and US thermal systems suggest 2–3 €/MWh for a penetration of 10 % and 3–4 €/MWh for higher penetration levels (Smith et al 2004; Dale et al, 2004; DTI, 2003)[8]. The figures may be exaggerated because the geographical smoothing effect is difficult to incorporate into wind power time series. In California, the incremental regulation costs for existing wind power capacity is estimated to 0.1 €/MWh, for wind energy penetration of about 2 % (Kirby et al, 2003).

Also the recently emerged electricity markets can be used to estimate the costs for hourly production and regulating power. An ideal market will result in the same cost effectiveness as the optimisation of the system in order to minimise costs. However, especially at an early stage of implementing a regulating market or due to market power, the market prices for regulation can differ from the real costs that the producers have.

[8] Currency exchange rate from the end of 2003 used: 1 € = 1.263 $; 1 € = 0.705 £

In a market-based study, Hirst (2002) estimated the increase in regulation (second/minute time scale) that would be necessary to maintain system reliability at the same level, before and after the implementation of wind power. The result was that the regulation cost for a large wind farm would be between 0.04 and 0.2 €/MWh. This result applies to systems where the cost of regulation is passed on to the individual generators, and not provided as a general service by the system operator.

In West Denmark, with a wind penetration of about 20 %, the cost for compensating forecast errors in day-ahead market at the regulating market amounted to almost 3 €/MWh [9].

In the electricity market, the costs for increased regulation requirements will be passed on to the consumers, and the production capacity providing for extra regulation will benefit from that. Regulation power nearly always costs more than the bulk power available on the market. The reason is that it is used during short intervals only, and that is has to be kept stand-by. Therefore, any power continuously produced by that capacity cannot be sold to the electricity spot market. The cost of reserves depends on what kind of production is used for regulation. Hydro power is the cheapest option and gas turbines are a more expensive one. The cost of extra reserves is important when the system needs an increasing amount of reserves, because of changes in the production or consumption, such as increased load. The costs of regulation may rise substantially and suddenly in a phase when the cheapest reserves have already been used and the more expensive new reserves have to be allocated.

The cost estimates for thermal systems include the price for new reserve capacity and assume a price for lower efficiency and part load operation. To fully integrate wind power into the system in an optimal way means using the characteristics and flexibility of all production units in a way that is optimal for the system. Also a wider range of options in order to increase flexibility can be used. Some examples for already existing technologies that could be used to absorb more variable energy sources are:

- Increased transmission between the areas or countries or synchronous systems.
- Demand-Side-Management (DSM) / Demand-Side-Bidding (DSB).
- Storage: thermal storage with CHP regulating, electrical storage can become cost-effective in the future, but is still expensive today.
- Making the electricity production of CHP units flexible by using alternatives for heat demand (heat pumps, electric heating, electric boilers).
- Short-term flexibility implemented in wind farms. When based on reducing the output of wind power, this means loss of production. The desired flexibility can be achieved more cost-efficiently by conventional generation, if it requires an extensive reduction of wind power output.

Even simple statistical independence makes different variable sources more valuable than just more of the same, such as wind power and solar energy. It may also be beneficial to combine wind power with energy limited plants where the maximum effect cannot be produced continuously because the availability of energy is limited. This is the case of hydro power and biomass. Power systems with large hydro power reservoirs have the option to use hydro power to smooth out the variability of wind power by shifting the time of energy delivery (Tande and Vogstad, 1999; Vogstad et al, 2000; Krau et al, 2002). This is possible also for short response times, within the operating constraints of flow and ramp rates of hydro power (Söder, 1999).

[9] See also chapter 10.

8.4.2 Other short-term effects

Other effects that wind power has at the operational level of the power system include its impact on losses in power systems (generation and transmission/distribution) and on the amount of fuel used and on emissions, e.g. CO_2. There is already technology which allows wind farms to benefit power system operation, e.g. by providing voltage management and reactive reserve (in the case of type D turbines that are connected to the network or in a limited way also in the case of type C turbines) as well as primary power regulation (Kristoffersson, 2002). This issue of reliability is not discussed in detail here.

Wind power can either decrease or increase the transmission and distribution losses, depending on where it is situated in relation to the load. However, large-scale wind power can result in an increased transmission between regions. That can lead to increased transmission losses or a larger number of bottlenecks in transmission[10]. For the UK, concentrating the wind power generation in the North would double the estimated extra transmission costs to 2 and 3 €/MWh at a penetration level of between 20 and 30 %. This would not be the case if production was more geographically dispersed (DTI, 2003). At more modest penetration levels, transmission costs would decrease.

Large amounts of intermittent wind power production can cause losses in conventional generation. The decreased efficiency of the system is caused by thermal or hydro plants operating below their optimum (starts, shutdowns, part load operation). The optimised unit commitment, i.e. planning the starts and shut-downs of slow-starting units, is complicated by the intermittent output from a wind resource. An accurate prediction of the wind power production will help to solve this problem. However, even with accurate predictions, the large variations in wind power output can result in conventional power plants operating in a less efficient way. The effect on existing thermal and/or hydro units can be estimated by simulating the system on an hourly basis. At low penetration levels, the impact of wind power is negligible or small (Grubb, 1991; Söder, 1994), although costs for large prediction errors in a thermal system have amounted to about 1 €/MWh (Smith et al, 2004)

If wind power production exceeds the amount that can be safely absorbed while still maintaining adequate reserves and dynamic control of the system, a part of the wind energy production may have to be curtailed. Energy is only discarded at substantial penetration levels. Whether such a measure is taken depends strongly on the operational strategy of the power system. The maximum production (installed capacity) of wind power is several times larger than the average power produced. This means that there are already some hours with nearly 100 % instant (power) penetration (wind power production equals demand during some hours), if about 20 % of yearly demand comes from wind power. There is experience from and studies on thermal systems that take in wind power production, but leave, even at high winds, the thermal plants running at partial load in order to provide regulation power. The results show that about 10 % (energy) penetration is the starting point where a curtailing of wind power may become necessary. When wind power production is about 20 % of yearly consumption, the amount of discarded energy will become substantial and about 10 % of the total wind power produced will be lost (Giebel, 2001;CER/OFREG NI, 2003). For a small thermal island system, e.g. on Crete, Greece, discarded energy can reach significant levels already at a penetration of 10 % (Papazoglou, 2002).

For other areas, integration problems may arise during windy periods, if production in the area exceeds demand and also transmission capacity to neighbouring systems. This can be especially pronounced during windy, cold periods when there is also a substantial share of local, prioritised combined heat and power (CHP) production, as is the case of

[10] See chapter 20

Denmark[11]. When initially in West Denmark wind energy was discarded, this happened at penetration levels of 20 % rather than 10 %. With energy system models it has been estimated, that by using the existing heat storage and boilers of CHP production units together with wind power, and assuming some flexible demand and electrical heating, a 50 % wind power penetration could be possible without discarding any energy (Lund & Münster, 2003).

Wind power is renewable energy, practically free from CO_2. CO_2 emissions from the manufacturing and construction are in the order of 10 gCO_2/kWh. If wind energy replaces generation that emits CO_2, CO_2 emissions from electricity production are reduced. The amount of CO_2 that will be abated depends on what production type and fuel is replaced at each hour of wind power generation. This will be the production form in use at each hour that has the highest marginal costs. Usually, this is the older coal fired plants, resulting in a CO_2 abatement of about 800–900 gCO_2/kWh, often cited as the CO_2 abatement of wind energy. This is also true for larger amounts of wind power production, for countries that generate their electricity mainly from coal. In other countries, though, there may be a different effect if large amounts of wind power are added to the system. There may not be a sufficient number of old coal plants whose capacity can be replaced by the wind power production throughout the year. During some hours of the year, wind power generation would replace other production forms, such as the production of gas fired plants (CO_2 emissions of gas are 400–600 gCO_2/kWh), or even CO_2 free production, e.g. hydro, biomass or nuclear power. Instant (regulated) hydro production can be postponed and will replace condensing power at a later instant. Simulations of the Nordic system, for example, which is a mixed system of thermal and hydro production, result in a CO_2 reduction of 700 gCO_2/kWh (Holttinen&Tuhkanen, 2004). This is the combined effect of wind power replacing other fuels.

8.4.3 Long-term effects on the adequacy of power capacity

The intermittent nature of wind energy poses challenges to utilities and system operators. These must be able to serve loads with a sufficiently low probability of failure. The economic, social and political costs of failing to provide adequate capacity to meet demand are so high that utilities have traditionally been reluctant to rely on intermittent resources for capacity.

Dimensioning the system for system adequacy usually involves estimations of the Loss-of-load-probability LOLP index. The risk at system level is the probability (LOLP) times the consequences of the event. For an electricity system, the consequences of a blackout are large, thus the risk is considered substantial even if the probability of the incident is small. The required reliability of the system is usually in the order of one larger blackout in 10–50 years.

What impact does wind power have on the adequacy of power production in the system – can wind power replace part of the (conventional) capacity in the system? For answering this question, it is critical we know wind power production during peak load situations. This also means that to assess the ability of wind power to replace conventional capacity, i.e. the capacity credits, it is important either to have representative data for several years (one year is not enough) or to make a variability assessment (Milligan, 2000; Giebel, 2001).

Some variable sources can be relied on to produce power at times of peak demand. Solar energy, for instance, follows air-conditioning loads and wind energy reflects heating demand. If a diurnal pattern in wind power production coincides with the load (e.g. wind

[11] See Chapter 10.

power production increases in the morning and decreases in the evening) this effect is beneficial. However, in most cases there is no correlation between load and the availability of this variable source. In Northern Europe, for example, even if the seasonal variations mean that more wind power is available in winter than in summer, there is not a strong correlation between the high loads in winter and high wind power production. In Denmark, the correlation is slightly positive (about 0.2), but there is usually less correlation during higher load winter months than in the summer months.

In Northern Europe, the load is strongly correlated to outside temperature. The correlation between wind power production and temperature has an effect on the adequacy of power production, when determining the capacity value of wind power (see figure 8.11). Looking at wind power production during the 10 highest peak load hours each year, it ranges between 7–60 % of capacity (years 1999–2001 in the Nordic countries, Holttinen, 2003).

Nevertheless, variable sources can save thermal capacity. Since no generating plant is completely reliable, there is always a finite risk of not having enough capacity available. Variable sources may be available at the critical moment when demand is high and many other units fail. Fuel source diversity can also reduce risk.

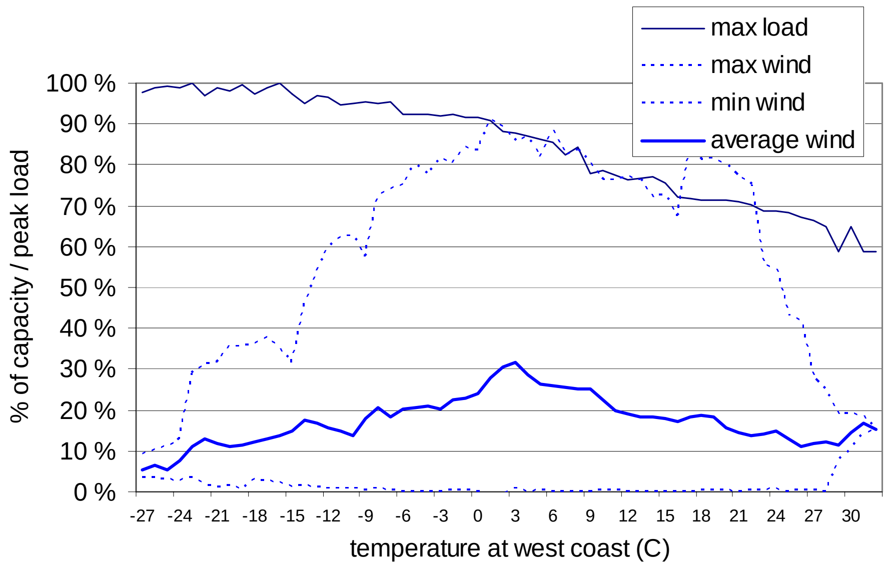

Figure 8.11 Correlation of temperature to wind power production and load in a cold climate, example of Finland, geographically dispersed wind power. There were 48 hours (0.1 % of time) below –23 °C and 549 hours (1.6 % of time) below –14°C during the years 1999–2002. (Source: Holttinen, 2003)

It has been shown in several studies that if the capacity of a variable source is small (low system penetration) the capacity value equals that of a completely reliable plant generating the same average power at times when the system could be at risk. As the penetration increases, variable sources become progressively less valuable for saving thermal capacity (DTI, 2003). The dispersion of wind power and a positive correlation between wind power and demand increase the value of wind power to the system. For very high penetration levels, the capacity credit tends towards a constant value, that is, there is no increase in the capacity credit when increasing wind power capacity. This will be determined by the LOLP without wind energy and the probability of zero wind power (Giebel, 2001).

If there is a substantial amount of wind power in the system (>5 % of peak load), an optimal system to accommodate wind power would contain more peaking and less base plants than a system without wind power. For hydro dominated systems, where the system is energy restricted instead of capacity restricted, wind power can have a significant energy delivery value. As wind energy correlates only weakly with hydro power production, wind energy added to the system can have a considerably higher energy delivery value than adding more hydro[12] (Söder, 1999).

8.4.4 Wind power in future power systems

Large-scale wind power still lies in the future for many countries. There are long-term trends that can influence the impact of wind power on the system. If there are large amounts of intermittent energy sources in the system, new capacity with lower investment costs (and higher fuel costs) will be favoured. The trend of increasing distributed generation from flexible gas turbines is beneficial for the integration of wind power, as is increasing load management. A greater system interconnection is highly beneficial as well: wind power spread all over Europe would be quite a reliable source. The use of electric vehicles will open new possibilities to variable and intermittent power production. Producing fuel for vehicles that are only used about 1,000 hours per year will ease the flexibility needs in power systems.

The expected developments of wind power technology will affect the impact that wind power has on the power systems. Very large wind farms (hundreds of MW) are one trend that can pose serious challenges to the integration of wind power, as they concentrate the capacity. As a result, the smoothing effect of variations by geographical spreading is lost. However, the large wind farms will also pave the way for other technologies that will help the integration. Increasingly sophisticated power electronics and computerised controls in wind farms, as well as an improved accuracy of wind forecasts will lead to improvements in the predictability and controllability of wind power. Large wind energy power plants will mean that there are new requirements regarding the integration of wind power into the power system. Increasingly, wind farms will be required to remain connected to the system when there are faults in the system. They will be expected to withstand nearby faults without experiencing problems in power production during and after the faults. And they will be expected to provide reactive power support to the system during the fault.

8.5 Conclusions

Wind power will have an impact on power system reserves as well as on losses in generation and transmission/distribution. It will also contribute to a reduction in fuel usage and emissions.

Regarding the power system, the drawbacks of wind power are that wind power production is variable, difficult to predict and cannot be taken for given. However, integrating variable sources is much less complicated if they are connected to large power systems, which can take advantage of the natural diversity of variable sources. A large geographical spreading of wind power will reduce variability, increase predictability and decrease the occasions with near zero or peak output. The power system has flexible mechanisms to follow the varying load that cannot always be accurately predicted. As no production unit is 100 % reliable, a part of the production can come from variable sources, with a similar risk level for the power system.

[12] See Chapter 9.

Power system size, generation capacity mix (inherent flexibility) and load variations have an effect on how intermittent production is assimilated into the system. If the proportion of intermittent power production is small, and wind power production is well dispersed over a large area, and correlates with the load, wind power is easier to integrate into the system.

Short-term, mainly the variations in wind power production affect power system operation. This refers to the allocation and use of extra reserves as well as cyclic losses of conventional power production units, and transmission/distribution network impacts. The area we have to look at for intra-hour variations is the synchronously operated system. In a large system, the reserve requirements of different loads and wind power interact and partly compensate each other. The power system operation then only needs to balance the resulting net regulation. The variability introduced by wind power will not be significant until variations are of the same order as the variability of the random behaviour of electricity consumers. On the time scale of seconds/minutes (primary control), the estimates for increased reserve requirement have resulted in a very small impact. On the time scale of 15 min to 1 h, the estimated increase in reserve requirement is of the order of 2–8 % of installed wind power capacity, when wind energy penetration level is 10 %.

Long-term, the expected wind power production at peak load hours has an impact on the power system adequacy. It is expressed as the capacity credit of wind power. For a low system penetration, the capacity credit equals that of a completely reliable plant generating the same average power at times when the system could be at risk. As the penetration increases, variable sources become progressively less valuable for saving thermal capacity.

There are no technical limits to the integration of wind power. However, as wind capacity increases, measures have to be taken to ensure that wind power variations do not reduce the reliability of power systems. There will be an increasing economic impact on the operation of a power system if wind power penetration exceeds 10 %.

Large-scale wind power still lies in the future for many countries, and there are long-term trends that can influence what impact wind power has on the system, like the use of electricity for vehicles, for instance. At high penetration levels, an optimal system may require changes in the conventional capacity mix.

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