WIND ENERGY - THE FACTS

PART II

GRID INTEGRATION

Acknowledgements

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II.1 SETTING THE SCENE

Wind Energy Penetration and Integration

In Part II, we consider the large-scale integration of wind energy in the context that wind will meet a substantial share of the European electricity demand in the future. While wind energy will cover around 4 per cent of electricity demand in 2008, EWEA targets for 2020 and 2030 estimate penetration levels of up to 14 per cent and up to 28 per cent respectively (EWEA, 2008a).

Europe's wind power resources are enormous and could easily cover a larger share of the electricity demand. This is already the case, notably in a few regions in Germany, Denmark and Spain. The key issue is how to develop the future power system so that wind power can be integrated efficiently and economically. Since integration efforts, such as costs and decision-making, are related directly to the penetration level of wind power, it is essential to have a commonly defined term. Wind energy penetration can be defined in a number of ways.

WIND ENERGY PENETRATION

This looks at the percentage of demand covered by wind energy in a certain region, normally on an annual basis (see Figure II.1.1).

Wind energy penetration (%)
= Total amount of wind energy produced (TWh) / Gross annual electricity demand (TWh)

WIND POWER CAPACITY PENETRATION

This looks at how the total installed wind power capacity in a certain region is related to the peak load in this region over a certain time period.

Wind capacity penetration (%)
= Installed wind power capacity (MW) / Peak load (MW)

MAXIMUM SHARE OF WIND POWER

This looks at the power balance in a certain region, taking into account the minimum demand, the maximum wind power generated and the exchange with neighbouring regions or countries. This figure must remain below 100 per cent to ensure the correct power balance in the region; the nearer to 100 per cent, the closer the system is to its limits (when wind power would need to be curtailed).

Maximum share of wind power
= Maximum wind power generated (MW) / Minimum load (MW) + power exchange capacity (MW)

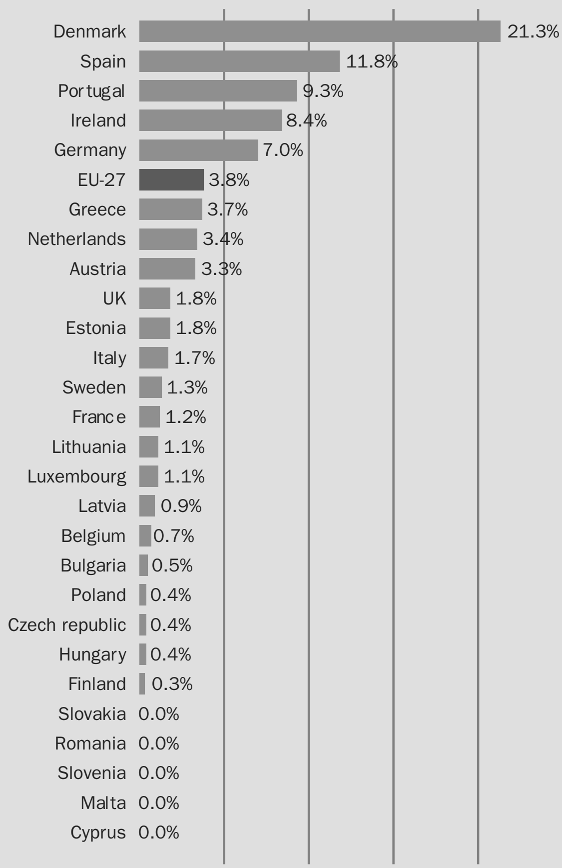
Throughout Part II, when reference is made to wind power penetration, the first definition will be used unless specified otherwise.

As shown in Figure II.1.1, the wind energy penetration levels vary throughout Europe. For the EU-27, the overall penetration in 2020 will be around 12–14 per cent according to present EWEA and European Commission (EC) targets.

Table II.1.1 shows the wind power capacity penetration values (second definition), at the beginning of 2007 for a number of countries in the Union for the Co-ordination of Transmission of Electricity (UCTE) area. These values are related to the reference load, as set out in the UCTE System Adequacy Forecast (January 2007). The installed wind power capacity refers to the situation at the end of 2006.

The share of wind power (third definition) is already high in certain areas of Europe, for example West Denmark (57 per cent) and the German state of

Figure II.1.1: Overview of wind energy penetration levels in Europe at the end of 2007



Source: EWEA (2008a)

Table II.1.1: Wind power capacity penetrations in various European countries

	Reference load (GW)	Wind power capacity (GW)	Capacity penetration
West Denmark	3.8	2.5	66%
Germany	74.0	20.6	28%
Spain	43.0	11.6	27%
Portugal	8.5	1.7	20%
The Netherlands	16.1	1.6	10%
France	80.0	1.6	2%

Source: EWEA

Schleswig-Holstein (44 per cent), but the system can absorb additional wind power before it reaches full capacity. However, with increasing amounts of wind power installed, improvements are required in the power exchange capacities between various countries. This will be discussed in more detail later in Part II.

European Policy Framework Relevant for Wind Power Integration

The electricity system in Europe needs to be modified in order to ensure security of supply, a fair and low electricity price for the consumer, and sustainable and climate-friendly electricity generation. These objectives form the basis of European energy policy. As wind power will play an ever more important role in the electricity supply, this section looks at some of the important policy developments at the EU level which are vital for the process of grid integration of wind power in Europe.

RENEWABLE ENERGY DIRECTIVE

A new Renewables Directive, agreed by the European Union in December 2008, sets a 20 per cent target for the EU as a whole for the share of energy demand to be covered by renewables by 2020. In order to achieve this target, the European Commission estimates that wind power will have to cover 12 per cent of total European electricity demand by 2020, although the individual national and sectoral targets have yet to be established. The Renewables Directive:

- stipulates that Member States take 'the appropriate steps to develop transmission and distribution grid infrastructure … to accommodate the further development' of renewable electricity; and
- includes a clause relating to priority or guaranteed access and priority dispatch for wind power and other renewables, on condition that the reliability and safety of the grid is maintained.

INTERNAL ELECTRICITY MARKET LEGISLATION

A series of legal measures (the so-called 'Third Liberalisation Package') were proposed in 2008. The intention is to create a single electricity market in Europe, with more coordinated regulation, improved system operation at international level and fair access for renewable energy sources (RES) generators. The measures include stronger international cooperation of transmission system operators (TSOs) under the European Network of Transmission System Operators for Electricity (ENTSO).

In principle, this could provide a changed framework for the future development of harmonised grid codes in the coming years. The implementation of the proposed Liberalisation Package could also improve the interconnection between Member States. The future Agency for the Coordination of Energy Regulators in Europe (ACER), as proposed by the Liberalisation Package, needs to ensure that TSOs submit appropriate transmission development plans and that the regulation in the market is improved, strengthened and harmonised.

THE TEN-E PROGRAMME

The Trans-European Energy Networks (TEN–E) programme addresses transmission development issues at the European level, in order to support the further development of the internal electricity market. A Green Paper on transmission issues was published in the third quarter of 2008, which will form the basis for European policies for transmission development and should give guidance on the national policy frameworks. The TEN-E programme is currently being complemented by a European Commission initiative to explore and possibly implement grid reinforcements, including offshore grid transmission lines to enable the connection of the predicted offshore wind power capacity. A European coordinator has been appointed for this purpose.

Brief Outline of the Main Integration Issues

Given the current levels of wind power connected to electricity systems, it is clearly feasible to integrate wind power to a significant extent without major system changes. The 60 GW of wind power already installed in Europe shows:

- areas of high, medium and low penetration levels;
- where different conditions exist; and
- where bottlenecks and challenges occur.

Wind power as a generation source has specific characteristics, including variability, geographical distribution, favourable economics, and, above all, abundance and environmental benefits. Large-scale integration of both onshore and offshore wind raises challenges for the various stakeholders involved, ranging from generation, transmission and distribution to power trading and consumers. In order to integrate wind power successfully, a number of issues need to be addressed in the following areas:

- **design and operation of the power system:** reserve capacities and balance management, short-term forecasting of wind power, demand-side management and storage, and optimisation of system flexibility;
- **grid infrastructure issues:** optimisation of present infrastructure, extensions and reinforcements, offshore grids, and improved interconnection;
- **grid connection of wind power:** grid codes, power quality and wind power plant capabilities;
- **market redesign issues:** market aggregation and adapted market rules increasing the market flexibility, particularly for cross-border exchange and operating the system closer to the delivery hour; and
- **institutional issues:** stakeholder incentives, non-discriminatory third party grid access and socialisation of costs.

II.2 WIND POWER VARIABILITY AND IMPACTS ON POWER SYSTEMS

A wind farm does not operate all the time, so backup capacity is needed for when it does not and differences between forecast and actual production have to be balanced. Balancing and backup come at a cost, as does building new infrastructure. These facts apply to wind energy just as they apply to other power producing technologies that we integrate into the electricity grids. But for reasons that are difficult to grasp, balancing and backup of wind energy is generally perceived to be problematic whereas balancing and backup for other technologies seems as easy as breathing. Certainly, most of the mainstream media does not find it interesting to report the complexities of balancing a constant supply of nuclear power or inflexible coal-fired power against the demand from millions of consumers, with their constantly changing and unpredictable demands for power.

There is nothing simple about operating a power grid. Delivering electricity to consumers is a logistical challenge larger than for any other product market. Transmission system operators (TSOs) are tasked with delivering an invisible product, which cannot be stored, to customers who expect to receive it at the exact same second they need it. Grid operation is just-in-time management in its most extreme form; when you think about it, it seems an unrealistic task for anybody to undertake. Nevertheless, European grid operators are simultaneously servicing 500 million fickle consumers with unpredictable behaviour every second of every hour of every day. They have done so for a hundred years with minimal supply disruption. If it was not for the fact that we experience it every day, we would say that it was impossible.

Just like an individual consumer, a wind turbine is variable in output and less predictable than most other technologies. However, from a system operations perspective, the supply behaviour of a single wind farm is just as irrelevant as the demand behaviour of a person. The collective behaviour of consumers and the collective behaviour of all generating plants are what matters. That has been the guiding principle of grid operation since its inception and is likely to remain so regardless of which technologies we use. If operating a grid is inherently difficult, we are fortunate in having system operators in Europe who understand what the rest of us find difficult to comprehend. Wind power is, admittedly, different from other power technologies, and integrating large amounts of it in the existing power system is a challenge. But whatever the generating technology, the basic principles of balancing, backing up, aggregation and forecasting still apply.

Changes to the way we construct and operate the future European electricity grids are still needed if we are to meet one-third of Europe's power demand with renewables within 12 years, as projected by the European Commission. But the challenge is by no means any greater or more costly than the one system operators faced when politicians thought that nuclear was the answer and expanded its share to 30 per cent of European demand in two decades. Today the answer happens to be wind, and of course the grid needs to be adapted to that new reality.

TSOs employ some of the most skilled people in the power sector. Nevertheless, they too need practical experience to acquire knowledge when new technologies are introduced in large amounts. European TSOs are gaining vast experience and knowledge about managing over 30 per cent wind power shares for long periods of time. In Denmark, a mind-blowing 140 per cent is sometimes managed.

Understanding Variable Output Characteristics of Wind Power: Variability and Predictability

WIND POWER: A VARIABLE OUTPUT SOURCE EMBEDDED IN A VARIABLE ELECTRICITY SYSTEM

Since wind energy is a technology of variable output, it needs to be considered as just one aspect of a variable, dynamic electricity system. At modest penetration levels, the variability of wind is dwarfed by the normal variations of the load. It is impossible to analyse wind power in isolation from other parts of the electricity system, and all systems differ. The size and the inherent flexibility of the power system are crucial aspects in determining the system's capacity to accommodate a large amount of wind power.

The variability of wind energy needs to be examined in the wider context of the power system, rather than at the individual wind farm or wind turbine level. The wind does not blow continuously at any particular site, but there is little overall impact if the wind stops blowing in a certain area, as it is always blowing elsewhere. This lack of correlation means that at the system level, wind can be harnessed to provide stable output regardless of the fact that wind is not available all the time at any particular site. So in terms of overall power supply, it is largely irrelevant to consider the curve when a wind power plant produces zero power for a time, due to local wind conditions. Moreover, until wind becomes a significant producer (supplying around 10 per cent of electricity demand), there is a negligible impact on net load variability.

Box II.2.1: Variable output versus intermittency

Wind power is sometimes incorrectly considered as an intermittent energy source; however, this is misleading. At power system level, wind power does not start and stop at irregular intervals (a characteristic of conventional generation), as is suggested by the term intermittent. Even in extreme conditions, such as storms, it takes hours for wind turbines in a system area to shut down, Moreover, periods with zero wind power production are predictable and the transition to zero power is gradual.

Also worthwhile considering is the technical availability of wind turbines, which is at a very high level (98 per cent) compared to other technologies. Another advantage of wind power in this respect is its modular and distributed installation in the power system. Breakdown of a single unit has a negligible effect on overall availability.

So, the term 'intermittent' is inappropriate for system-wide wind power and the term 'variable output' should be used instead.

Wind power varies over time, mainly under the influence of meteorological fluctuations. The variations occur on all timescales: seconds, minutes, hours, days, months, seasons and years. Understanding these variations and their predictability is of key importance for the integration and optimal utilisation of wind in the power system. Electric power systems are inherently variable in terms of both demand and supply, but they are designed to cope effectively with these variations through their configuration, control systems and interconnection.

SHORT-TERM VARIABILITY

The analysis of data available from operating wind farms and meteorological measurements at typical wind farm locations allows us to quantify the variations in net wind power output that can be expected for a given time period (within the minute or hour, or during the course of several hours). The distinction between these specific timescales is made since this type of information corresponds to the various types of power plants for balancing. The results from analyses show that the power system can handle this short-term variability well. System operators only need to deal with the net output of large groups of wind farms, and the wind power variability is viewed in relation to the level and variation in power demand.

Variations within the Minute

The fast variations (seconds to minute) of aggregated wind power output (as a consequence of turbulence or transient events) are quite small, due to the aggregation of wind turbines and wind farms, and hardly impact the system.

Variations within the Hour

The variations within an hour are much more significant for the system. However, they should always be considered in relation to demand fluctuations. Local variations are largely equal to geographical diversity, and will generally remain inside ±5 per cent of installed wind power capacity at the regional level.

The most significant variations arise from the passage of storm fronts, when wind turbines reach their storm limit (cut-out wind speed) and shut down rapidly from full to zero power. However, due to the averaging effect across a wind farm, the overall power output takes several minutes to reduce to zero. And in general, this is only significant in relatively small geographical areas, since in larger areas it takes hours for the wind power capacity to cease during a storm. For example, in Denmark – a small geographical area – on 8 January 2005, during one of the biggest storms for decades, it took six hours for the installed wind power in the West Denmark area to drop from 2000 to 200 MW (5 MW/minute) (see Figure II.2.1). The passage of a storm front can be predicted and technical solutions are available to reduce the steep gradient, such as the provision of wind turbines with storm control.[1]

These intra-hour variations will be an issue for power system reserves used for balancing when wind power penetration reaches the point at which variations in supply are equal to variations in demand (when 5–10 per cent of annual electricity demand is produced by wind power).

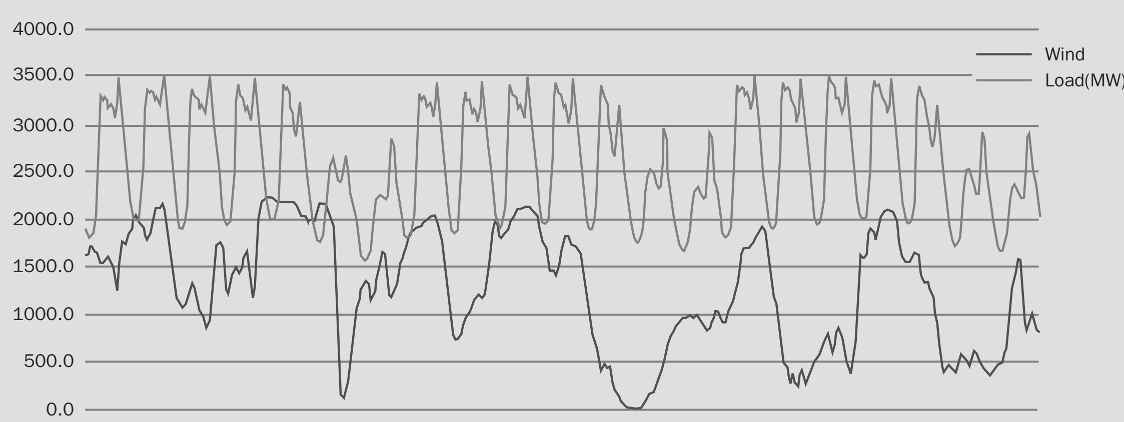
Variations from Hour to Hour

The variations between forecast and actual wind energy production several hours ahead affect the scheduling of the power system. For system operation, the variation in itself is not a problem; it is the uncertainty of how accurately the variation can be predicted that is significant. The uncertainty of wind power predictions should always be considered in relation to the errors in demand forecasts. There is much work being conducted in this area and it is clear that solutions are available.

LONG-TERM VARIABILITY

The slower or long-term variations of wind power relevant for integration in the power system include the seasonal and inter-annual variations, caused by climatic effects. These are not particularly important for

Figure II.2.1: Denmark: The storm on 8 January is recorded between hours 128 and 139



Source: www.energinet.dk

the daily operation and management of the grid, but play a role in strategic power system planning.

Monthly and Seasonal Variations

These variations are important for electricity traders that have to deal with electricity forward contracts, where wind power volume has an influence on price. They are also important for power system planning. However, it appears that for both electricity trading and system planning purposes, these deviations, resulting from annual statistics of wind power produced, can be sufficiently hedged.

Inter-annual Variations

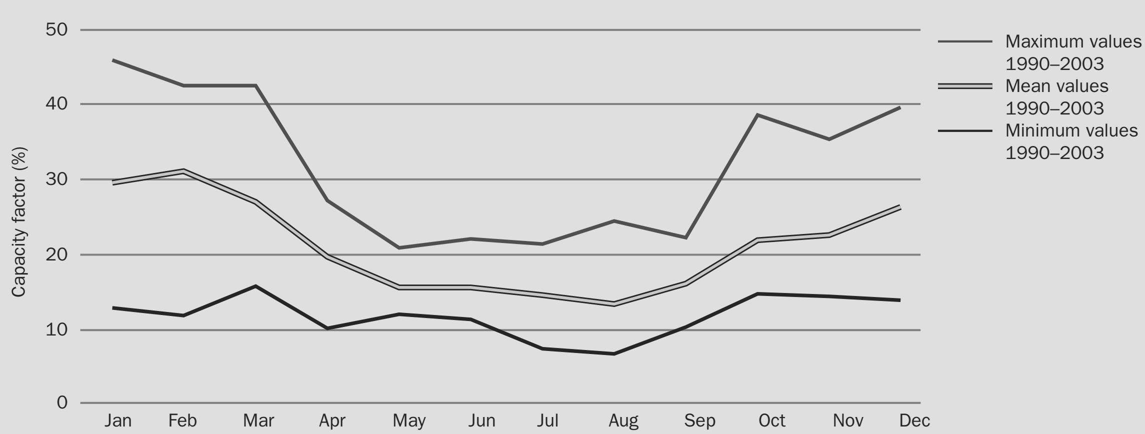
These variations are relevant for long-term system planning, rather than daily power system operation. The annual variability of long-term mean wind speeds at sites across Europe tends to be similar, and can be characterised by a normal distribution with a standard deviation of 6 per cent. The inter-annual variability of the wind resource is less than the variability of hydro inflow. In addition, at the power system level, the annual variations are influenced by the market growth of wind power and the projected onshore/offshore ratio.

EFFECTS OF AGGREGATION AND GEOGRAPHICAL DISPERSION

Due to the wide regional distribution of wind plants, short-term and local wind fluctuations are not correlated and therefore largely balance each other out. As a result, the maximum amplitudes of wind power fluctuations experienced in the power system are reduced. This phenomenon has been extensively studied throughout Europe.

Whereas a single wind farm can exhibit hour to hour power swings of up to 60 per cent of capacity, the maximum hourly variation of 350 MW of aggregated wind farms in Germany does not exceed 20 per cent (ISET, 2004). For larger areas, such as the Nordel system, which covers four countries, the largest hourly variations would be less than 10 per cent of installed

Figure II.2.2: Average, maximum and minimum values of monthly capacity factors, Germany, 1990–2003, showing the long-term pattern of wind power variability



Source: ISET (2004)

wind power capacity if the capacity was distributed throughout all the countries. The geographical spread of wind farms across a power system is a highly effective way to deal with the issue of short-term variability: the more widespread the wind farms, the lower the impact from variability on system operation.

The effect of reduced wind power variability increases with the size of the area considered. Ideally, to maximise the smoothening effect, the wind speeds occurring in different parts of the system should be as uncorrelated as possible. Due to the typical sizes of weather patterns, the scale of aggregation needed to absorb a storm front is in the order of 1500 km. By aggregating wind power over large regions of Europe, the system can benefit from the complementarities of cyclones and anticyclones over Europe (Figure II.2.3). The economic case for smoothing wind power fluctuations by utilising transmission capacity (rather than by other means) is an important area of investigation, for example in the TradeWind project.[2]

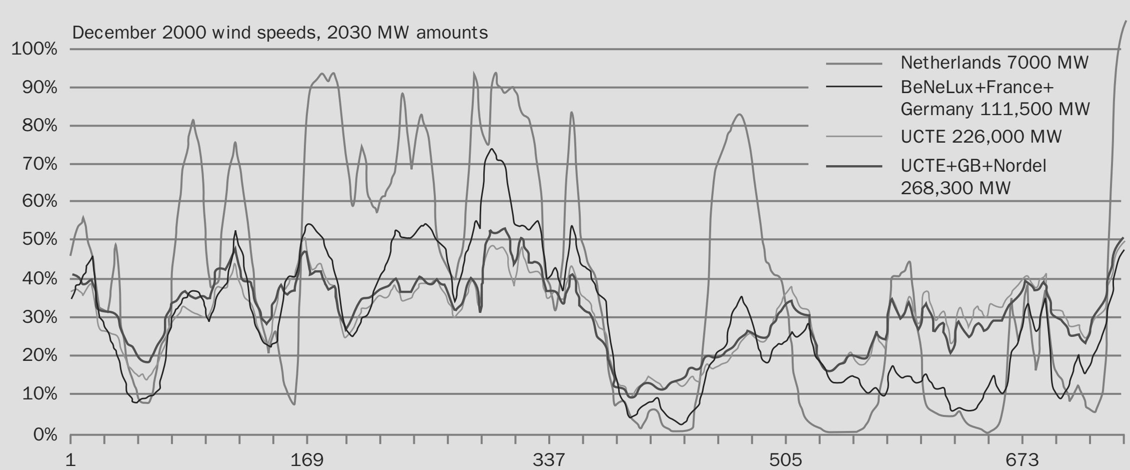
In addition to the advantage of reducing the fluctuations, the effect of geographically aggregating wind farm output is an increased amount of firm wind power capacity in the system. This will be explained further in Chapter II.6.

LOAD DURATION CURVE

One method of representing the smoothing effect of aggregation on system scale is the load duration curve of wind farms, which gives the frequency distribution of the partial load states of generated wind power (see Figure II.2.5). The effect of aggregating wind power is a flattening of the duration curve. This means that when wind power is aggregated over a large area:

- the effective number of hours when wind power is available increases; and
- the number of hours with zero or low power diminishes, while the maximum value of instantaneous aggregated power produced is decreasing.

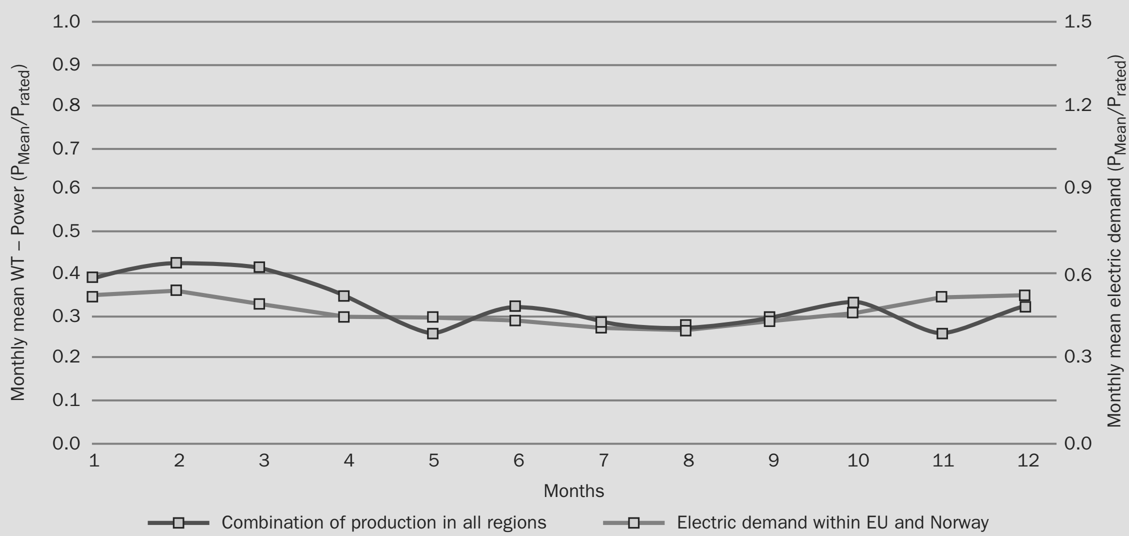
Figure II.2.3: Example of smoothing effect by geographical dispersion



Note: The figure compares the hourly output of wind power capacity in four situations, calculated with simulated wind power. The simulations are based on December 2000 wind speeds and wind power capacity estimated for the year 2030.

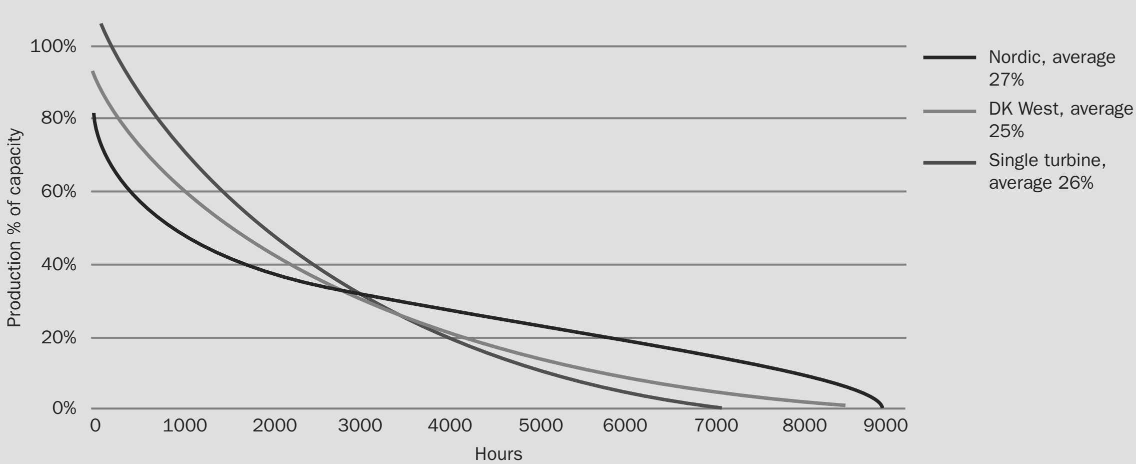
Source: www.trade-wind.eu

Figure II.2.4: Combined wind energy production from Europe and Northern Africa (Morocco) produces a monthly pattern that matches demand in Europe and Norway



Source: Czisch (2001)

Figure II.2.5: Duration curves for the 'wind year 2000', Denmark and Nordic countries, assuming equal wind capacity in each of the four countries



Source: Holttinen et al. (2007)

As part of the TradeWind project, a simulation was made for the EU-27, with an assumed wind capacity distribution for 2020 and 2030. The effect of geographical aggregation means that the maximum aggregated instantaneous wind power is only 60 per cent of the total capacity of 200 GW (Tande et al., 2008).

THE NEED FOR INTERCONNECTION

It is impossible to optimally aggregate large-scale wind power without a suitably interconnected grid. In this context, the grid plays a crucial role in aggregating the various wind farm outputs installed at a variety of geographical locations, with different weather patterns. The larger the integrated grid – especially beyond national borders – the more pronounced this effect becomes. This effect is equivalent to using the grid to aggregate demand over interconnected areas. In order to make best use of this effect, the present transmission system in Europe needs to be upgraded. Ideally, the interconnection capacity should be increased, and the rules governing the power exchange between countries should be adapted to ensure that interconnectors are always available for physical flow.

Variability Versus Predictability of Wind Power Production

Accurate forecasts of the likely wind power output, in the time intervals relevant for generation and transmission capacity scheduling, allow system operators and dispatch personnel to manage the variability of wind power in the system. Predictability is key to managing wind power's variability and improved accuracy of wind power prediction has a beneficial effect on the amount of balancing reserves needed, so the accurate forecasting of wind power is important for its economic integration into the power system.

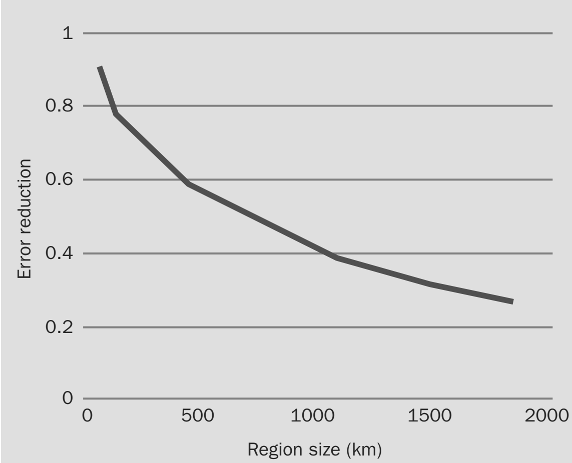
Today, wind energy forecasting uses sophisticated numerical weather forecast models, wind power plant generation models and statistical methods to predict generation at 5-minute to 1-hour intervals, over periods of up to 48 to 72 hours in advance and for seasonal and annual periods.

Forecasting wind power production differs from forecasting other generation forms or forecasting the load.[3] Wind, being a natural phenomenon, is better suited to reliable statistical treatment and physical forecasting than conventional plants which are subject to physical faults.

Wind power prediction can be quite accurate for aggregated wind power, as the variations are levelled out; and the larger the area, the better the overall prediction. The extent to which prediction error decreases with the size of the region[4] considered is shown in Figure II.2.6. It should be noted that the forecast accuracy is reduced for longer prediction periods.

The quality of the short-term forecast should be considered in relation to the gate closure times in the power market. Reducing the time needed between scheduling supply to the market and actual delivery

Figure II.2.6: Decrease of forecast error of prediction for aggregated wind power production, due to spatial smoothing effect



Source: Energy and Meteo Systems

(gate closure time) would allow shorter-term forecasts to be used, which could dramatically reduce unpredicted variability and lead to more efficient system operation without compromising system security. Changing from day-ahead to intraday commitments has a dramatic impact on accuracy and the cost of balancing the system. It is important to understand that for system operation, it is not just wind forecasting accuracy that is relevant for balancing the system, but also the sum of all demand and supply forecast errors relevant for system operation.

Impacts of Wind Power on Power Systems

The impacts of wind power in the electricity system depend to a large extent on the:

- level of wind power penetration;
- grid size; and
- generation mix of electricity in the system.

Wind energy penetration at low to moderate levels is a matter of cost, as demonstrated by various national and regional integration studies. And the integration costs related to the impacts listed above are fairly modest.

For low penetration levels of wind power in a system, system operation will hardly be affected. Currently (in 2008) wind power supplies less than 4 per cent of the overall EU electricity demand, but there are large regional and national differences in penetration, as shown in Figure II.1.1.

The established control methods and system reserves available for dealing with variable demand and supply are more than adequate for dealing with the additional variability at wind energy penetration levels of up to around 20 per cent, depending on the nature of a specific system. For higher penetration levels, some changes to systems and their method of operation may be required to accommodate the further integration of wind energy.

SHORT- AND LONG-TERM IMPACTS

The impacts of wind power on the power system can be categorised into short- and long-term effects. The short-term effects are caused by balancing the system at the operational timescale (minutes to hours), whereas the long-term effects are related to the contribution wind power can provide to the system adequacy (its capability to reliably meet peak load situations).

IMPACTS IN THE SYSTEM: LOCAL AND SYSTEM-WIDE

Locally, wind power plants interact with the grid voltage, just like any other power station. In this context, steady-state voltage deviations, power quality and voltage control at or near wind farm sites must all be taken into consideration. Wind power can provide voltage control and active power (frequency) control. Wind power plants can also reduce transmission and distribution losses when applied as embedded generation.

On the system-wide scale, there are other aspects to consider.

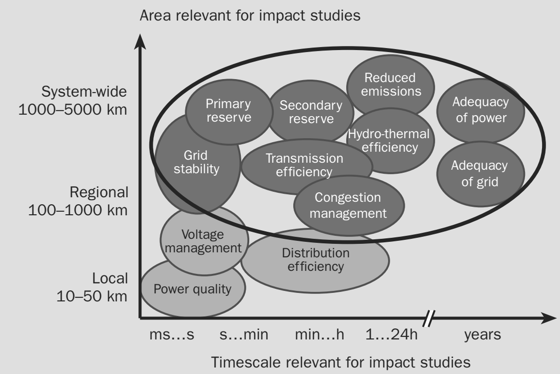
- Wind power plants affect voltage levels and power flows in the networks. These effects can be beneficial to the system, especially when wind power plants are located near load centres, and certainly at low penetration levels. For example, wind power plants can support the voltage in the system during fault (low voltage) situations. Also, wind plants that have a reactive power control system installed at the end of long radial lines benefit the system, since they support the voltage in (normally) low voltage quality parts of the grid.
- Wind power may need additional upgrades in transmission and distribution grid infrastructure, as is the case when any power plant is connected to a grid. In order to connect remote high-resource sites, such as offshore wind farms or very large wind plants in remote areas, to the load centres, new

lines need to be constructed (just as new pipelines had to be built for oil and gas). In order to maximise the smoothing effects of geographically distributed wind, and to increase the level of firm power, additional cross-border transmission is necessary to reduce the challenges of managing a system with high levels of wind power.

- Wind power requires measures for regulating control, just like any other generation technology, and, depending on the penetration level and local network characteristics, it affects the efficiency of other generators in the system (and vice versa).
- In the absence of sufficient intelligent and well-managed power exchange between regions or countries, a combination of (non-manageable) system demands and production may result in situations where wind generation has to be constrained.
- Finally, wind power plays a role in maintaining system stability and contributes to the system adequacy and security of supply.

For an overview and categorisation of the power system effects of wind power, see Table II.2.1 below.

Figure II.2.7: System impacts of wind power



Note: Issues which are within the scope of Task 25 are circled in black.

Source: Holttinen et al. (2007)

A graphical overview of the various impacts of wind power in the power system is given in Figure II.2.7. It shows the local and system-wide impacts, as well as the short- and long-term impacts, for the various affected aspects of the power system, which include grid infrastructure, system reserves and system adequacy.

Table II.2.1: Power system impacts of wind power causing integration costs

	Effect or impacted element	Area	Timescale	Wind power contribution
Short-term effects	Voltage management	Local/regional	Seconds/minutes	Wind farms can provide (dynamic) voltage support (design dependent).
	Production efficiency of thermal and hydro	System	1–24 hours	Impact depends on how the system is operated and on the use of short-term forecasting.
	Transmission and distribution efficiency	System or local	1–24 hours	Depending on penetration level, wind farms may create additional investment costs or benefits. Spatially distributed wind energy can reduce network losses.
	Regulating reserves	System	Several minutes to hours	Wind power can partially contribute to primary and secondary control.
	Discarded (wind) energy	System	Hours	Wind power may exceed the amount the system can absorb at very high penetrations.
Long-term effects	System reliability (generation and transmission adequacy)	System	Years	Wind power can contribute (capacity credit) to power system adequacy.

Source: EWEA

II.3 DESIGN AND OPERATION OF EUROPEAN POWER SYSTEMS WITH LARGE AMOUNTS OF WIND POWER

In order to integrate wind power efficiently at higher levels of penetration, changes to the operating methods of various parts of the power system, such as generators and transmission systems, are required. Moreover, active management at the demand side of the power system can be used to facilitate wind power integration. Wind power, with its variable output characteristics, affects other generators in the system. As well as reducing their required output, wind power also requires other plants in the system to be scheduled differently.

In order to efficiently integrate large amounts of wind power, it is essential for the system design to be more flexible, which can be achieved by a combination of:

- flexible generating units;
- flexibility on the demand side;
- availability of interconnection capacity; and
- more flexible rules in the power market.

Balancing Demand, Conventional Generation and Wind Power

EFFECT OF WIND POWER ON SCHEDULING OF RESERVES

In this section, we outline the way in which wind affects the operation of the other generators in the system. Further information on power system operating principles is provided in Appendix H.

Primary Reserves

Wind power development will have little or no influence on the amount of primary reserves required. On second/minute timescales, rapid variations in the total wind power capacity output occur randomly, such as existing load variations. When aggregated with load and generation variations, the increase in variability due to wind is very small. Furthermore, the amount of primary reserve allocated in the power systems is dominated by potential outages of large thermal generation plants, meaning it can easily cope with these rapid variations.

Secondary and Tertiary Reserves

The impact of wind power on the need for secondary reserves will only be increasingly significant from wind energy penetrations levels of 10 per cent upwards. The main impact of wind power will be on how conventional units are scheduled to follow load (hour to day timescales). If the output from a wind plant could be accurately predicted one to two days in advance, schedulers could more easily determine units that would need to be committed. The lack of an accurate forecast adds further uncertainty to the commitment decision, on top of the uncertainty associated with load forecasting. The result is that a unit might be unnecessarily committed, or that it may not be committed when this is required. In this case, the generation mix of the power system determines scheduling in view of expected wind power production – the greater the flexibility of power units, the later unit commitment decisions can be made.

The estimate for extra reserve requirements due to wind power (EWEA, 2005a; Holttinen et al., 2007) is in the order of 2–4 per cent of the installed wind power capacity at 10 per cent penetration of gross consumption, depending on how far ahead wind power forecast errors are corrected by reserves (this is dependent on the gate closure times).

Short-term Forecasting of Wind in System Operation

Clearly, short-term forecasting becomes increasingly important for system operation as wind power penetration increases. In regions with high penetration levels, such as certain areas of Spain, Germany, Denmark and

Ireland, wind farm operators routinely forecast output from their wind farms. These forecasts are used by system operators to schedule the operation of other plant and for trading purposes. The benefits of the application of short-term forecasting depend, to a large extent, on national regulatory, technological and site-specific issues. The main advantages are cost reductions and improved system security.

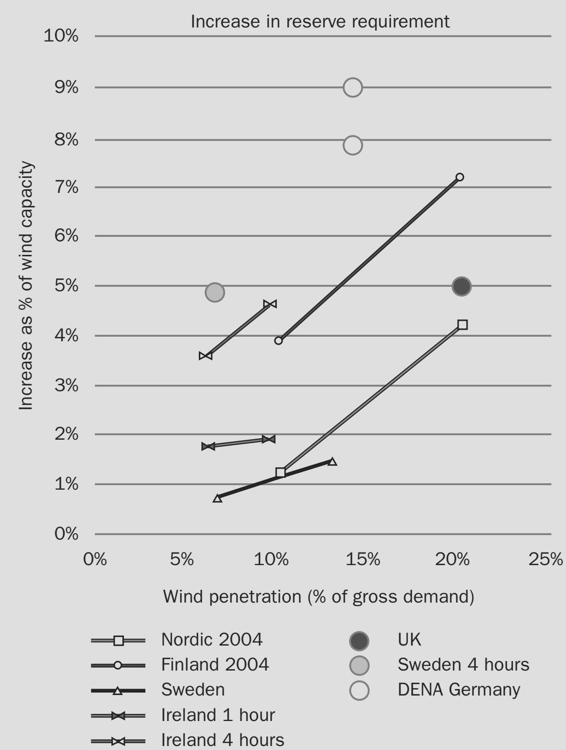
ADDITIONAL BALANCING CAPACITIES AND BALANCING COSTS: OVERALL RESULTS FROM SYSTEM STUDIES

The amount of additional reserve capacity and the corresponding costs associated with increasing wind power penetration are being explored in many countries by means of system studies carried out by power engineers. This involves the simulation of system operation, whereby the effect of increasing amounts of wind power is analysed for different scenarios of generation mix. In 2006, international cooperation was established under the IEA's Task 25 to compare and analyse the outcome of different national system studies. Task 25's first report provides general conclusions, based on studies from Denmark, Finland, Norway, Sweden, Germany, Ireland, Spain, The Netherlands, Portugal, the UK and the US.

Both the allocation and the use of reserves imply additional costs. The consensus from most studies carried out so far is that the extra reserve requirements needed for larger wind power penetrations are already available from conventional power plants in the system, so in fact no new reserves are required. This means that only the increased use of dedicated reserves, or increased part-load plant requirement, will create extra costs for the energy part.

The studies calculate additional costs, compared to a situation without wind power. Most results are based on comparing the costs of system operation without wind power and then adding varying amounts of wind power into the equation (see Figure II.3.1). The costs of variability are also addressed, by comparing simulations assuming constant (flat) wind energy to those with varying wind energy.

Figure II.3.1: Results for the increase in reserve requirement due to wind power, as summarised by IEA Task 25



Note: Major factors explaining the difference in results between various studies are assumptions with respect to forecast uncertainties (resulting from length of forecast horizon/gate closure time) and the geographical size of the area considered.

Source: Holttinen et al. (2007)

Estimates of the extra cost of reserves (mainly secondary load-following reserves) suggest €1–4/MWh for a wind power penetration of up to 10 per cent of gross consumption. This cost is normalised per MWh of wind energy produced. The cost per MWh at the consumption level is around €0.1–0.4/MWh at 10 per cent wind energy penetration, which is typically around 0.1 per cent of the electricity consumption price. These findings indicate that the additional system operation costs, in terms of balancing additional variability due to large-scale integration of wind power, are only a small fraction (typically less than 10 per cent) of the generation costs of wind power. The effect on the consumer price is close to zero.[5]

System Operation Aspects

TRANSMISSION LEVEL

Balancing and securing system operation by the transmission system operator (TSO) involves the use of transmission lines in the system area and interconnections to neighbouring systems. The issues include congestion management, priority access and priorities in curtailment in critical situations, such as low demand or high winds.

High penetration levels of wind power production affect the operation of the transmission system. Voltage control in the system may be required (for example near large wind farms) in order to cope with unwanted voltage changes, which might be enhanced by variable output wind power. This voltage support could be supplied by the wind farm if adequate wind energy technology were to be used; otherwise dedicated equipment would need to be installed, such as FACTS devices.[6]

Another issue is the management of power flows and possible congestion in the grid. Specific combinations of both the level and geographical location of wind power production and demand can cause changes in the size and direction of power flows in the transmission grid. This results in changing cross-border flows. In order to manage these cross-border power flows, TSOs also need high-quality wind forecasting tools. FACTS devices and phase-shifting transformers may be used for the management of power flows.

DISTRIBUTION LEVEL

Until now, the connection of wind power to the grid has usually been at distribution level. A particular feature of distribution grids is that there is no active management, for example, at transmission level. The distribution grids have to cope with greater distributed generation levels, without reducing the quality of supply to other customers.

The ‘embedded generation’ of wind power benefits the grid: weak grids may be supported by wind power, and users on the line may be better served, as wind power can help to control grid voltage. Power electronics of wind farms can also improve power quality characteristics in the grid. The power, if consumed within the distribution network, goes directly to the user and transmission costs can be reduced. Finally, depending on the grid code requirements of the relevant control area, wind power may maintain operations in parts of the system in the event of transmission failures, which would otherwise cause blackouts.

Adding wind power to distribution grids results in similar effects as in the transmission grid: a change in the direction and quantity of real (active) and reactive power flows, which may interact with the operation of grid control and protection equipment. The design and operation practices at the distribution level may need to be modified as additional distributed generation, such as wind power, is added. Distribution grids may have to become more ‘actively managed’, which would require the development of suitable equipment and design principles. However, the improved grid brings collateral benefits to the distribution grid operator.

WIND POWER CLUSTER MANAGEMENT

The pooling of several large wind farms into clusters in the GW range provides new options for optimising the integration of variable output generation into electricity supply systems. Concepts for cluster management (Rohrig et al., 2004; Estanqueiro et al., 2008) include the aggregation of geographically dispersed wind farms, according to various criteria, for optimised network management and (conventional) generation scheduling. The clusters will be operated and controlled in the same way as large conventional power plants.

The implementation of these operating methods will significantly increase wind energy's economic value to the system, by keeping additional costs for balancing to a minimum. Based on innovative wind farm operational control, a control unit between system operators and wind farm clusters (so-called 'wind farm cluster management', WFCM) will enable a profile-based generation. WFCM combines and adjusts wind plant control systems, based on forecasts, operating data, online-acquired power output and defaults from system operators.

Options for Increasing Power System Flexibility

The availability of flexible balancing solutions (generation capabilities, load management and energy storage) in power systems is an important facilitating factor for the integration of wind power. Even though power system balancing is not new, wind power provides new challenges at high penetration levels, since its variable nature requires additional flexibility in the power system – the capability to adequately respond to fast and significant net system load variations.

By increasing the flexibility of the power system, its ability to integrate variable output generation can be enhanced. In a more flexible system (for example systems with large amounts of hydro- or gas-powered electricity), the effort required to reach a certain wind energy penetration level can be lower than in a less flexible system (for example systems with a high share of nuclear power). In a system that covers a larger geographical area, a larger amount of flexibility sources are usually available. The differences in the size of power systems, dispatching principles and system flexibility explain the differences in integration costs in different countries. For example, Denmark has a high level of flexibility as it is well interconnected, thus enabling a high penetration level without significant additional costs. Portugal is another example of a flexible power system enabling easy and low-cost wind power integration, due to the large amount of fast responding, reversible hydropower plants in the system.

A serious consideration in the planning to integrate substantial amounts of wind power is the provision (flexibility sources) for additional flexibility needs in the system, compared to a situation without wind power. In the assessment of the required additional flexibility, a distinction has to be made in the different market timescales (hour/day ahead).

The main sources for additional flexibility are:

- fast markets (markets with short gate closure times);
- flexible generation (for example gas and hydro);
- demand-side management (DSM);
- energy storage; and
- interconnection.

Fast Markets

There is considerable diversity in European power market rules, but day-ahead markets exist in most countries. The day-ahead forecast error for wind has been significantly reduced in recent years, due to improved weather forecast models, but the error is still higher than for intraday forecasts. In the interest of wind power integration, gate closure times should be reduced, in order to minimise forecasting uncertainty, and therefore reducing last-minute balancing adjustments. Organising markets throughout Europe to operate faster and on shorter gate closure times (typically three hours ahead) would favour the economic integration of wind power.

A recent study (Milligan and Kirby, 2008), based on the situation in the state of Minnesota in the US, calculates the savings in balance power that could be achieved by balancing areas and assuming the presence of an energy market with a five-minute re-dispatch. In the hourly timescale, balance area consolidation reduces ramp requirements of balancing plants by 10 per cent, while in the five-minute timescale this reduction is double – more than 20 per cent. This has considerable effects on the balancing costs, and thus on the integration of wind power.

Flexible Generation

Existing balancing solutions mostly involve conventional generation units: hydropower, pumped hydro and thermal units. Hydropower is commonly regarded as a very fast way of reducing power imbalance, due to its fast ramp-up and ramp-down rates. It also has a marginal cost, close to zero, making it a very competitive solution. Pumped hydro accumulation storage (PAC, see below) also allows energy storage, making it possible to buy cheap electricity during low-load hours and to sell it when demand and prices are higher.

Of course, thermal units are also commonly used for power system balancing (primary control and secondary control). In the category of thermal generation, gas-fired units are often considered to be most flexible, allowing rapid production adjustments. There is also potential in making existing power plants more flexible.

Storage Options

There is increasing interest in both large-scale storage implemented at transmission level and smaller-scale dedicated storage embedded in distribution networks. The range of storage technologies is potentially wide. For large-scale storage, PAC is the most common and best-known technology. PAC can also be set up underground.

Another large-scale technology option is compressed-air energy storage (CAES). On a decentralised scale, storage options include:

- flywheels;
- batteries (lead-acid and advanced), possibly in combination with electric vehicles;
- fuel cells (including regenerative fuel cells, 'redox systems');
- electrolysis (for example hydrogen for powering engine-generators or fuel cells); and
- super-capacitors.

An attractive solution would be the installation of heat boilers at selected combined heat and power (CHP) locations, in order to increase the operational flexibility of these units.

Storage involves a loss of energy. If a country does not have favourable geographical conditions for hydro reservoirs, storage is not the first solution to look at due to the poor economics at moderate wind power penetration levels (up to 20 per cent). In certain cases, it can even have an adverse effect on system operation with respect to CO_2 emissions (Ummels et al., 2008). In fact, the use of storage to balance variations at wind plant level is neither necessary nor economically viable.

Demand-side Management

With demand-side management (DSM), loads are controlled to respond to power imbalances by reducing or increasing power demand. Part of the demand can be time-shifted (for example heating or cooling) or simply switched off or on according to price signals. This enables a new balance between generation and consumption, without the need to adjust generation levels.

Today, the adjustment of generation levels is more common than DSM. The availability of this solution depends on load management possibilities (for example in industrial processes such as steel treatment) and the financial benefits offered by flexible load contracts (cost of power cuts and power increases versus lower bills). Attractive demand-side solutions in combination with decentralised storage are:

- heat pumps combined with heat boilers (at domestic or district level);
- cooling machines combined with cold storage; and
- plug-in electric vehicles.

Each of these solutions permits the separation of the time of consumption of electricity from the use of the appliance, by means of storage.

Interconnection

Available interconnection capacity for exchange of power between countries is a significant source of flexibility in a power system. However, the capacity should be technically as well as commercially available. Data on available interconnection capacities are published at www.etso-net.org. See also the section on interconnection on page 164.

II.4 GRID INFRASTRUCTURE UPGRADE FOR LARGE-SCALE INTEGRATION

European Transmission and Distribution Networks

Electricity networks can be split into two major subsections: transmission networks and distribution networks.

TRANSMISSION NETWORKS

The transmission network usually consists of high to very high voltage power lines designed to transfer bulk power from major generators to areas of demand; in general, the higher the voltage, the larger the transfer capacity. Only the largest customers are connected to the transmission network.

Transmission network voltages are typically above 100 kV. The networks are designed to be extremely robust, so they can continue to fulfil their function even in the event of several simultaneous network failures. Failure of a single element, such as a transformer or transmission line, is referred to as an 'N-1' event, and transmission systems should be capable of withstanding any such events. More complex cases of simultaneous failures of multiple elements (for example the failure of a transmission line when a parallel line has been disconnected for maintenance), are termed 'N-2' or similar. Transmission systems should also be capable of withstanding any such credible combinations.

Transmission consists mainly of overhead lines. Although underground lines offer the advantages of being less visually intrusive and raising less environmental objections, they incur higher initial investment costs and have a lower transmission capacity.

Transmission systems are operated by transmission system operators (TSOs) or independent system operators (ISOs). Responsibility for constructing or owning the physical network may belong to other organisations.

Transmission systems are actively managed through power system control centres, also known as dispatch centres. Balancing power entering and leaving the high voltage network, and reconfiguring the network to cope with planned and forced outages, is a 24-hour activity.

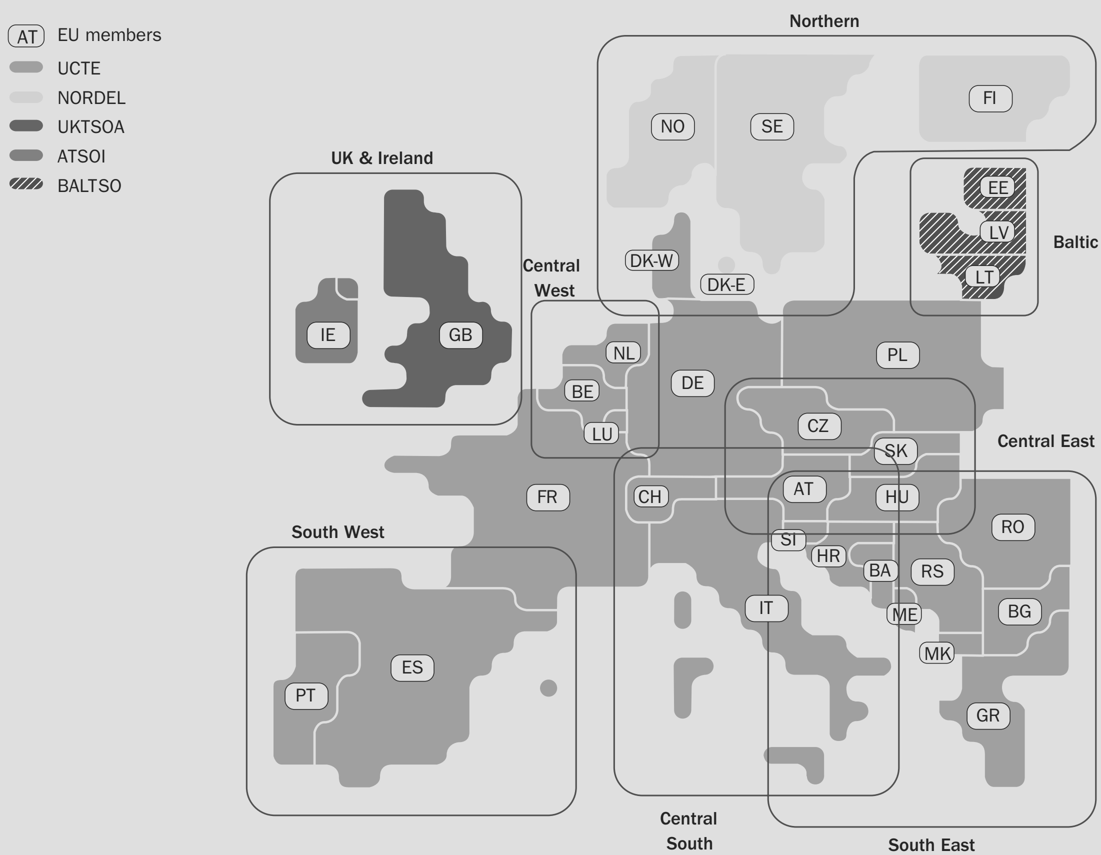
The European grid (Figure II.4.1) is divided into five synchronous regions and five relevant organisations: NORDEL (Organisation for the Nordic Transmission System Operators), BALTSO (Cooperation Organization of Estonian, Latvian and Lithuanian Transmission System Operators), UKTSOA (United Kingdom Transmission System Operators), ATSOI (Association of Transmission System Operators in Ireland) and UCTE (Union for the Co-ordination of Transmission of Electricity). Each of these organisations coordinates the TSOs involved at both operational and planning stages. The creation of the future European Network for Transmission System Operators for Electricity (ENTSO-E) will provide a new framework aimed at facilitating coordination between the different areas.

DISTRIBUTION NETWORKS

Distribution networks are usually below 100 kV and their purpose is to distribute power from the transmission network to customers. At present, with the exception of wind and other renewable power plants, little generation is connected to distribution networks, but this is changing rapidly, for example in Germany and Denmark.

Generation connected to distribution networks is often termed 'embedded generation' or 'distributed generation'. Distribution networks are less robust than transmission networks and their reliability decreases as voltage levels decrease. For example, a connection at 33 kV could expect to lose only a few minutes of connection per year on average, whereas a low voltage connection at 230 V for an individual domestic consumer

Figure II.4.1: Different synchronous regions in Europe



Source: UCTE Transmission Development Plan 2008

in a rural area would, on average, expect to lose at least an hour. As with transmission networks, distribution networks are operated (in some cases also owned) by distribution system operators (DSOs).

There is very little 'active' management of distribution networks. Rather, they assume a 'fit and forget' philosophy, in other words they are designed and configured on the basis of extreme combinations of circumstances (for example maximum demand in conjunction with high ambient temperatures, which reduce the capacity of overhead lines), to ensure that even in these extreme circumstances the network conditions experienced by customers are still within agreed limits.

Network Planning for Wind Power: Benefits of and Options for Increasing Transmission Capacity

THE NEED FOR IMPROVED NETWORKS

Liberalisation, market conditions, technology and the environment create fundamental changes and challenges for the European transmission and distribution networks. One of the major drivers is the emerging internal electricity market in Europe, which requires an adequate transport capacity between control regions and Member States to enable effective competition and trade of physical electricity. Therefore, enhancing the suitability of the grid for increased transnational and regional electricity transport is both in the interest of the wind industry and crucial for the development of the internal electricity market.

In addition, the specific nature of wind energy as a distributed and variable-output generation source requires specific infrastructure investments and the implementation of new technology and grid management concepts. The impacts of wind power on transmission, as described in Chapter II.2 (and see Figure II.2.1), are related to grid stability, congestion management, and transmission efficiency and adequacy. The large-scale integration of wind power requires a substantial increase in transmission capacity and other upgrade measures within and between the European Member States.

IMPROVING NETWORKS FOR INTEGRATING WIND POWER

The typical additional grid improvement measures required at increasing levels of wind power penetration can be classified into the following categories, in order of increasing effort and cost.

Soft Measures

In the short term, and at relatively low levels of wind power penetration, transmission upgrades coincide to a large extent with methods for congestion management and optimisation in the transmission system. Soft measures do not involve extensive expenditure, but rather avoid or postpone network investments.

The utilisation of existing power lines can often be increased by operating them at a higher capacity, assisted by temperature monitoring. Improving the cross-border electricity exchange procedures, and thus the manner in which power is flowing between different countries, is also a method for alleviating congestion. If controllable power plants are available within the congested area, coordinated automatic generation control (AGC) may be applied. DSM, controlled according to the wind energy and transmission situation, is another option. Applying control systems that limit the wind power generation during critical hours should be considered as a last resort, because it is both environmentally and economically inefficient.

Investments Other Than the Construction of New Lines

At significant penetration levels, there is a need for additional voltage management in the grids, which can be achieved by devices such as FACTS[6] and also by the technical capabilities of the wind farms themselves, in particular with technologies that enable expanded MVAR capabilities.[7]

Studies in the UK (Strbac et al., 2007) have concluded that it may be preferable to insist on sufficient fault ride-through (FRT)[8] capability from large wind power plants. In certain cases, and in order to ensure power system security at higher penetration levels, this would be more economical than modifying the power system operation and not insisting on FRT capability from wind turbines.

It can be argued that the additional costs associated with the improved wind power plant capabilities at the wind farm level should also be materialised, such as in the 2008 amendment of the German Renewable Energy Law.

There are several ways in which the transmission capacity of the network can be increased (UCTE, 2008). These include:

- adding transformers to existing substations, thus enabling a higher load feed and in some cases evacuating higher generated power;

- upgrading assets: for example operating a line at higher voltage (within its design limits) or increasing the transmission capacity of a power line by tightening the conductors and reinforcing the towers;
- installing new facilities in grid substations to improve the distribution of power flows among different parallel paths and to fit better with the line capacities: for example series reactors, phase-shifting transformers or devices to increase voltage support (shunt reactive devices and static VAR compensators);
- improving the utilisation of existing assets when possible: for example replacing line conductors with high temperature conductors or adding a second circuit on an existing line (within the design limit of the towers); and
- replacing existing assets with those of a higher transmission capacity: for example replacing an existing 225 kV line with a 400 kV double-circuit line.

Construction of New Lines

Grid reinforcement is necessary to maintain adequate transmission as wind power penetration increases. This reinforcement is preceded by extensive power system analysis, including both steady-state load flow and dynamic system stability analysis. The construction of new lines is also a prerequisite for reaching regions with a high wind resource, for example offshore locations. Nowadays, in many areas of Europe, the construction of new overhead lines may take as long as 10 to 12 years from the initial concept to implementation, mainly because of lengthy planning and permission procedures.

Several studies at national and European level are now underway to back up the plans for upgrading the European transmission system in order to facilitate large-scale integration. The most important international studies are the European Wind Integration Study (EWIS) and TradeWind, which will provide recommendations in 2009. Initiated in 2007, EWIS investigates the grid measures necessary to enable the wind power capacity foreseen for 2015 in a cooperative effort between European TSOs. The EWEA-coordinated project, TradeWind, started in 2006 and investigates the grid upgrade scenarios at the European level that would be necessary to enable wind energy penetration of up to 25 per cent, using wind power capacity scenarios up to 2030.

ENSURING ADEQUATE TRANSMISSION CAPACITY AND ACCESS FOR WIND POWER

From the above, it can be seen that in order to integrate wind power, sufficient transmission capacity needs to be available to carry the power to the demand centres. This capacity must be provided by transmission lines and a proper legal framework for accessing this capacity is required.

At the European level, two major initiatives contain basic elements of such a framework (see also 'European policy framework relevant for wind power integration' in Chapter II.1):

- The newly agreed European Renewable Energy Directive (2008) stipulates that national governments and TSOs should guarantee sufficient transmission capacity and fair access for renewables to the transmission network.
- The mandatory ownership unbundling of generation and transmission, as required by the proposed Third Energy Package (2008), should provide the legal basis to guarantee a level playing field with other generators.

In practice, the construction of the required network upgrades, especially new lines, is a very lengthy process. Also, because of the difference in speed between wind power development and transmission development, there is a need to implement fair access rules for cases where lines have to be shared between wind and other generators. As yet, there are no established rules at the European level and grid access for wind energy is presently solved in a rather pragmatic way. Some countries, such as Germany and Spain, take into account the recommendations from the 2001 RES Directive, and grant priority access to wind power to a certain extent. In practice, in case available grid capacity is limited, the principle of 'connect and manage' is often used.

INTEGRATING WIND POWER IN DISTRIBUTION NETWORKS

The addition of embedded generation, such as wind power, to distribution networks is quite common and was at the origin of wind power development in most countries. However, when wind generation reaches very high levels, it brings new challenges, for the following reasons:

- The distributed generation adds a further set of circumstances (full generation/no generation) with which the network must cope without negatively affecting the quality of supply seen by customers.
- The direction and quantity of real and reactive power flows change, which may affect the operation of network control and protection equipment at local level.
- Design and operational practices are no longer suitable and may need to be modified.

In contrast to these challenges, distributed generation systems (DGSs) also bring benefits to distribution networks, including:

- a reduction in network losses in many situations; and
- the avoidance of network reinforcement which would otherwise be required to achieve standards for quality of supply.

To address these issues, distribution networks may become more 'actively managed'. This implies cost and requires the development of suitable equipment and design principles. Active management of the networks by DSOs may be assisted by introducing new concepts, such as 'clusters of wind farms' that aggregate and enable the monitoring of generation (see also page 161). In the future, it is expected that distributed wind generation will be fully controlled and operated as a virtual power station (VPS).

Transnational Offshore Grids

THE CASE FOR AN OFFSHORE GRID

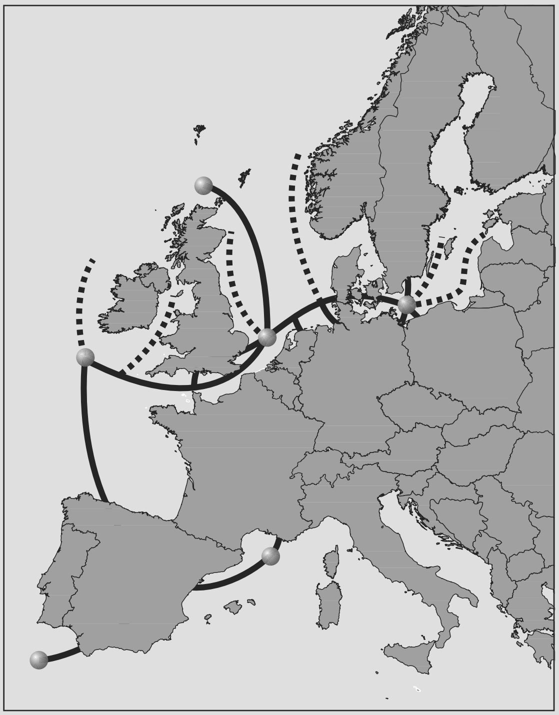
The exploitation of the offshore wind potential in Europe brings new challenges and opportunities for European power transmission. The long-term European offshore potential amounts to up to 150 GW in 2030, according to EWEA estimates in 2008. The majority of the currently projected offshore wind plants will be situated close to the European coastlines, not further than 100 km from the shore, due to the high costs of grid connection, limited grid availability and the lack of regulatory frameworks. Looking at the North Sea alone, with a potential of hundreds of GW of wind power, an offshore grid connecting different Member States would enable the transfer of this wind power to load centres and, at the same time, facilitate the competition and the trade of electricity between countries. A multi-terminal offshore grid would reach offshore wind plants far from shore, as foreseen for German and UK waters.

The project developer Airtricity introduced the offshore Supergrid® concept in 2005. Supergrid® combines the following:

- the connection of offshore wind plants;
- the balancing of wind power variations; and
- the provision of transmission of electricity between different markets for cross-border trade.

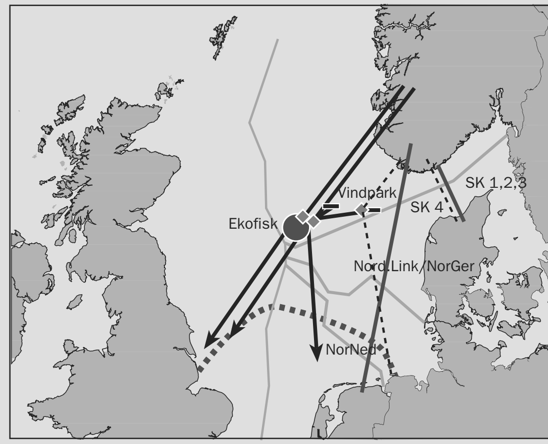
A commercial proposal has been worked out for a first phase of 10 GW of wind power – the construction

Figure II.4.2: Vision of high voltage 'super grid' to transmit wind power through Europe



Source: Dowling and Hurley (2004)

Figure II.4.3: Offshore grid proposal by Statnett



Source: Statnett (2008)

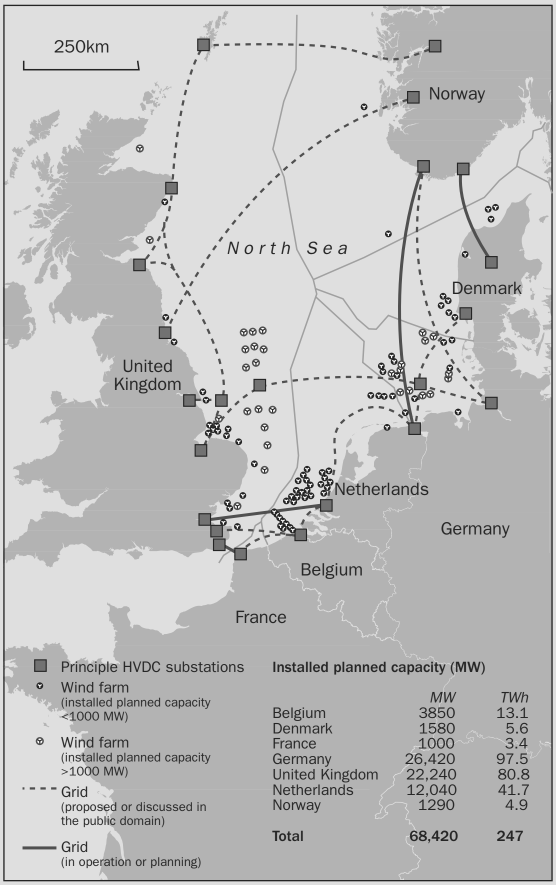
of an offshore 'super grid' which would be on a modular basis. The fact that wind farms will be able to operate collectively at variable speed and frequency, independent of the land-based grid, is expected to optimise turbine generating efficiency and offset losses incurred as a result of the increased transmission distances.

At first, large, multi-GW offshore arrays would connect to nearby networks, before being modularly extended and ultimately interconnected. A further advantage of this system will be the full controllability of power flows, eventually allowing an 'all-European' market for electricity, including 'firm' wind power.

Presently, the idea of a transnational offshore grid is being addressed by several other parties. The Norwegian TSO Statnett proposes the progressive development of a grid linking Scandinavia with UK, Germany and The Netherlands (Figure II.4.3). On its way, it would connect offshore wind farms, as well as existing offshore oil installations that need to reduce their CO_2 emissions. The technology to be used is a HVDC VSC (see 'Ensuring adequate transmission capacity and access for wind power' above).

Greenpeace (Woyte et al., 2008) has studied the concept of an offshore grid serving electricity trade between European countries around the North Sea and at the same time providing transmission of up to 70 GW of offshore wind power capacity – a target that could be achieved between 2020 and 2030 (Figure II.4.4). The study has also evaluated the smoothing effect of aggregating the offshore wind power using such a grid. The offshore grid topology proposed seeks the maximum synergy between existing plans and reinforcements, aiming to improve the cross-border exchange between countries. For example, it includes the East Connector in the UK, which alleviates the heavy north–south congestions, as well as an offshore connection along the French, Belgian and Dutch coasts.

Figure II.4.4: Offshore grid examined in the Greenpeace study



Installed planned capacity (MW)

	MW	TWh
Belgium	3850	13.1
Denmark	1580	5.6
France	1000	3.4
Germany	26,420	97.5
United Kingdom	22,240	80.8
Netherlands	12,040	41.7
Norway	1290	4.9
Total	**68,420**	**247**

Source: Woyte et al. (2008)

The effects of grid configurations described above on the power flows in the European transmission system are being analysed in the TradeWind project. A common element to all these proposals is the fact that the offshore grid would provide multiple functions and serve the functioning of the European electricity market. Therefore, it should be considered as an extension of the existing onshore grid, falling under the responsibility of the various governments, TSOs and regulators involved.

TECHNICAL SOLUTIONS FOR THE OFFSHORE GRID

Compared to onshore sites, offshore wind farms will have large power capacities and be comparable in size to conventional power plants, typically in excess of 400 MW. Modern transmission technologies operating at high and extra high voltage levels will be required to transmit high levels of power over longer distances. Two main types of offshore transmission systems exist, based on either alternating or direct currents (HVAC or HVDC).

For wind farms close to shore, the HVAC system offers the best solution, as it provides the simplest, least expensive and proven technology for grid connection and is similar to the transmission network used on land. However, as transmission distances increase, the losses from the HVAC system increase significantly. To avoid ineffective operation, AC cable length should be limited to a length of approximately 120 km. HVDC technology offers a number of advantages, but has a distinct investment cost structure, as it involves the installation of expensive converter stations. The break-even distance (now around 90 km) depends on the cost developments, and will move closer to the shore as HVDC system costs decrease.

Conventional thyristor-based HVDC technology has generally been used for point-to-point power transmission. Offshore wind farm arrays would benefit from a multi-terminal transnational offshore grid system. Recent advances in HVDC technology, using insulated gate bipolar transistor (IGBT)-based converters, seem to offer a solution and facilitate the cost-effective construction of multi-terminal HVDC networks. These modern HVDC-IGBT systems offer clear technological advantages, especially in the area of controllability and efficiency. A specific advantage of HVDC systems is reactive power control capability, favouring grid integration and system stability. The technical and economic aspects of offshore transmission systems are being actively investigated by the supply industry and by electric power companies in order to be ready with the most cost-effective solutions when large-scale offshore wind power takes off.

Coordinated Network Planning at the European Level

Besides the grid upgrades required in various countries in view of the integration of wind power, there is also the need for a coordinated effort in network planning at the European level. At higher wind energy penetration levels, cross-border power flow will increase, which:

- reduces wind power variability;
- improves the predictability of wind power;
- reduces balancing costs; and
- increases wind energy's contribution to the generation adequacy.

However, this increased cross-border flow increases the need for coordinated network planning and common technical regulations. In this respect, there are several relevant ongoing initiatives and developments:

- The Trans-European Energy Networks (TEN-E) programme was set up to promote the improvement of interconnection in Europe. Coordinated by the European Commission (DG TREN), TEN-E focuses on those network aspects that improve electricity trade within Europe. Several bottlenecks in the transmission system have been identified by TEN-E as projects of European interest. Despite the launch of this programme, however, though with a few exceptions, there has been little progress in increasing interconnection capacity. In 2007, as part of the measures proposed in the Priority Interconnection Plan of the European Energy Policy, a specific European Coordinator was appointed by the European Commission with the mandate to mediate in the interconnection projects required to enable the integration of wind power in northern Europe.
- As recommended in the Third Energy Package in 2008, the European Transmission Operators founded a new organisation, the European Network of Transmission System Operators for Energy (ENTSO-E), with the aim of improving the coordination of their operations. Another Third Package requirement is the obligation for joint TSOs to publish a transmission development plan (UCTE, 2008) on a regular basis.
- Within the EWIS study (FP6), The European TSOs are currently examining the technical and market aspects that will arise from wind power integration (time horizon 2015) in the European transmission system. This should result in recommendations for transmission planning at the European level. The TradeWind project coordinated by EWEA, which runs in parallel with EWIS, will provide recommendations for interconnection and power market improvements with a time horizon of up to 2030, at which point 300 GW of wind power is expected to be integrated in Europe. Having established a common platform for the exchange of information and findings, both EWIS and TradeWind will provide quantitative input for coordinated transmission planning for the future of wind power.

II.5 GRID CONNECTION REQUIREMENTS

Regulatory and Legal Background

All customers connected to a public electricity network, whether generators or consumers, must comply with agreed technical requirements, in order for the network to operate safely and efficiently. Electricity networks rely on generators to provide many of the control functions, and so the technical requirements for generators are unavoidably more complex than for demand customers.

These technical requirements are often termed 'grid codes', though the term should be used with care, as there are often different codes, depending on the voltage level of connection, or the size of the project. Also, there may be technical requirements that are not referred to in the grid code, but which apply to the project through the connection agreement or the power purchase agreement or in some other way.

The purpose of these technical requirements is to define the technical characteristics and obligations of generators and the system operator, meaning that:

- electricity system operators can be confident that their system will be secure regardless of the generation projects and technologies applied;
- the amount of project-specific technical negotiation and design is minimised;
- equipment manufacturers can design their equipment in the knowledge that the requirements are clearly defined and will not change without warning or consultation;
- project developers have a wider range of equipment suppliers to choose from;
- equivalent projects are treated fairly; and
- different generator technologies are treated equally.

In the past, with vertically integrated utilities, the same organisation was responsible for the planning and operation of networks and generators, so the technical requirements did not need to be particularly clearly defined or fair. Nowadays, in order to avoid distortions of competition and to comply with a liberalised energy market in Europe, there is a trend towards the legal separation of generators and system owners/operators. As a result, the technical requirements governing the relationship between generators and system operators need to be more clearly defined. The introduction of renewable generation has often complicated this process significantly, as these generators have physical characteristics that are different from the directly connected synchronous generators used in large conventional power plants. In some countries, this problem has caused significant delays in the development of fair grid code requirements for wind generation.

In some countries, a specific grid code has been produced for wind farms, and in others, the aim has been to define the requirements as far as possible in a way which is independent of the power plant technology.

There are benefits to requirements that are as general as possible, such as treating all projects equally. However, this can result in small projects facing the same requirements as the largest projects, which may not be technically justifiable.

Requirements are usually written by the system operator, often overseen by the energy regulator body or government. The requirement modification process should be transparent and include consultation with generators, system users, equipment suppliers and other affected parties.

Wind Power Plant Capabilities

Wind turbine technology is discussed in detail in Part I. Turbine technology is also covered briefly in this section, to provide some background to the information that follows.

The traditional Danish stall-regulated wind turbine concept uses an induction generator. Its rotational speed is fixed by the frequency of the electricity network to which it is connected. The blades are fixed – in other words do not pitch – so the output power and structural loads in high winds are limited by passive stall regulation. Unfortunately, this concept, though cheap, simple and reliable, has several negative effects on the electricity network:

- lack of power control, meaning that system frequency cannot be controlled; this is achieved relatively simply by conventional power plants;
- limited control of reactive power, making it more difficult to control network voltages; and
- during network disturbances (such as a sudden fault on the network), a wind turbine is likely to aggravate the situation.

The fixed-speed, pitch-regulated concept (in other words the possibility to control active power output by pitching the blades) resolves the first of these issues, and the limitations of the stall-regulated wind turbine concepts can be mitigated with the addition of terminal equipment in the substation.

The development of variable-speed wind turbines, using power electronic converters, was undertaken largely to reduce mechanical loads. This introduces additional control of reactive power as a by-product, and in the majority of cases also reduces the wind turbine's effect on the network during a sudden fault.

The larger the power electronic converter (relative to the size of the wind turbine), the greater the control over reactive power. So variable-speed, pitch-regulated wind turbines, based on the full-converter principle, now allow the desired control of wind turbines within the required limits.

The currently available wind turbines do not make full use of this capability, however, and grid codes do not yet take advantage of the full capabilities. As wind penetration increases, and network operators gain experience with the behaviour of their systems, grid codes will possibly become more demanding. New technical requirements should be based on:

- a detailed assessment of requirements;
- the technical potential of all the power plant's technology; and
- the optimal way in which to meet these demands, both technically and economically.

Grid Codes and Essential Requirements for Wind Power Plants

The arrangement of the technical requirements within grid codes and related documents varies between electricity systems. However, for simplicity the typical requirements for generators can be grouped as follows:

- tolerance – the range of conditions on the electricity system for which wind farms must continue to operate;
- control of reactive power – often this includes requirements to contribute to voltage control on the network;
- control of active power;
- protective devices; and
- power quality.

It is important to note that these requirements are often specified at the point of common coupling (PCC) between the wind farm and the electricity network. In this case, the requirements are placed at the wind farm level, and wind turbines may be adapted to meet them. Often, wind turbine manufacturers specify the performance of their wind turbines, rather than that of the entire wind farm.

It is also possible for some requirements to be met by providing additional equipment, separate from the turbines; this is indicated, where relevant, in the following discussion.

TOLERANCE

The wind farm must continue to operate between minimum and maximum voltage limits. Usually, this is stated as steady-state quantities, though short-term limits are not unknown (in other words a wider range may apply for a limited duration).

The wind farm must also continue to operate between minimum and maximum frequency limits. Often there is a range which applies continuously, and several further more extreme short-term ranges.

In systems with relatively high wind penetration levels, a common requirement is for wind farms to continue to operate during severe system disturbances, during which the voltage can drop to very low levels for very short periods of time. This is termed 'fault ride-through' (FRT) or 'low voltage ride-through'. The requirements can be complex, and depend on the technical characteristics of the electricity system. Proving compliance with the requirements may be difficult and costly.

It is feasible to use wind turbines that do not comply with FRT requirements, and to meet these requirements by installing additional equipment which can produce or consume reactive power at turbine level, or centrally within the wind farm.

REACTIVE POWER CONTROL

Reactive power production and consumption by generators allows the network operator to control voltages throughout their system. The requirements can be stated in a number of ways.

The simplest is the fixed power factor. The wind farm is required to operate at a fixed power factor when generating, often equal to 1. Often, the required accuracy and integration intervals for the verification of the power factor are not stated. And the fixed value may be changed occasionally, for example for winter and summer or peak and no-load periods.

Alternatively, the wind farm may have to adjust its reactive power consumption or production in order to control the voltage to a set point. This is usually the voltage at the PCC, but other locations may be specified. There may be requirements on the accuracy of control and the speed of response. Fast control may be difficult to achieve, depending on the capabilities of the wind farm's SCADA communications system.

Some wind turbine designs can fulfil these functions, even when the wind turbine is not generating. This is potentially a very useful function for network operators, but is not yet a common requirement.

FRT requirements can be met with central reactive power compensation equipment.

ACTIVE POWER CONTROL

With pitch-regulated turbines, it is possible to reduce the output at any moment by pitching the blades. This could also be done with stall-regulated turbines, by shutting down individual turbines within a wind farm. Although this only provides relatively crude control, the output from the power system operator's point of view is effective and valuable.

All forms of active power control in a wind turbine require a reduction in output power, which means a reduction in revenue. This is less of an issue for conventional power stations, where the lost revenue will be compensated, to some extent, by a reduction in fuel cost. Therefore, system operators and energy regulators recognise that a reduction in wind farm output should be used as a last resort.

The simplest method is a cap, which means that the wind farm (or a group of wind farms) is instructed to keep its output below a certain level. A more complex version of the cap is to insist that output is kept at a fixed level (delta), below the unconstrained output available from wind.

In parallel with a cap, the wind farm may also be instructed to control ramp rate, in other words to limit the rate at which the output power can increase (due to increasing wind speed or turbines returning to service after some outage). The ramp rate is defined over periods of, for example, one minute or ten minutes. This limits the network operator's demands on other forms of generation to adjust output rapidly.

Clearly, it is not possible for wind generation to control automatically the 'negative ramp rate' if the wind drops suddenly. However, with good wind forecasting tools, it is possible to predict a reduction in wind speed in advance; the output of the wind generation can then be gradually reduced in advance of the wind speed reduction, thereby keeping the negative ramp rate at an acceptable level.

In systems with relatively high wind penetration, there is often a requirement for frequency response or frequency control. This can take many forms, but the basic principle is that, when instructed, the wind farm reduces its output power by a few per cent, and then adjusts it in response to the system frequency. By increasing power when frequency is low, or decreasing power when frequency is high, the wind farm can contribute to controlling the system frequency.

PROTECTIVE DEVICES

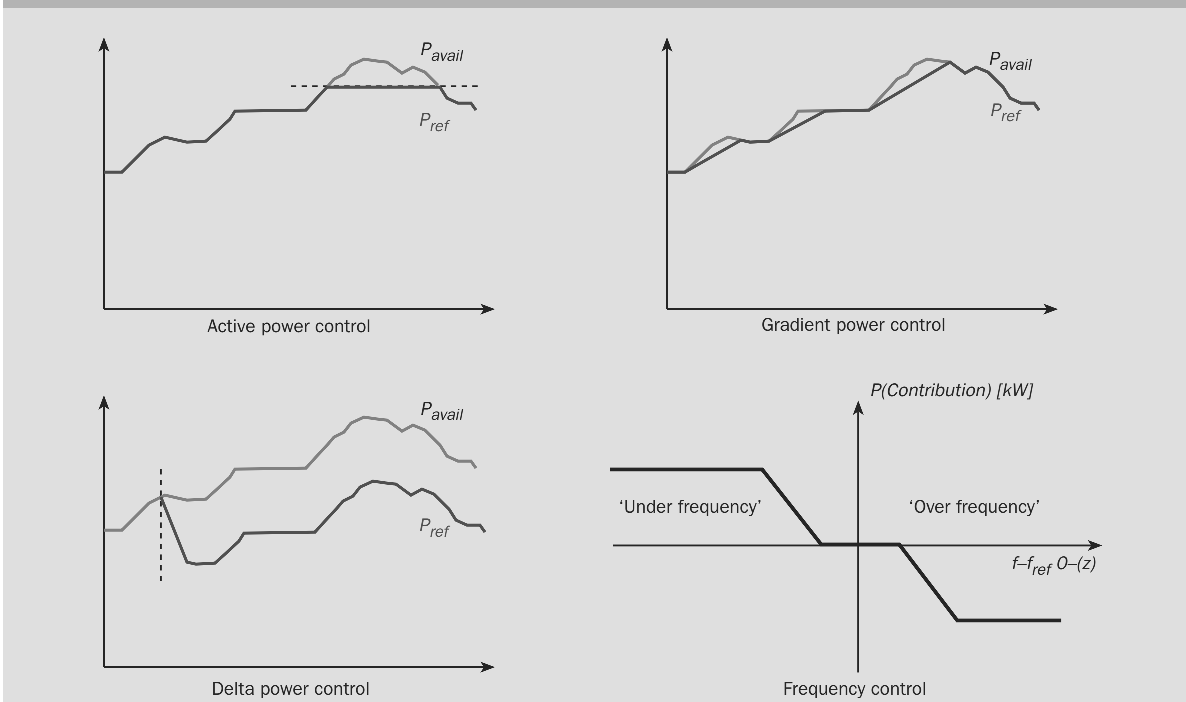
Protective devices, such as relays, fuses and circuit breakers are required to protect the wind farm and the network from electrical faults. Careful coordination may be needed to ensure that all conceivable faults are dealt with safely, and that correctly functioning equipment is not disconnected unnecessarily.

Short-circuit (or fault) current is a related issue. In the event of an electrical fault on the network close to the wind farm, some short-circuit current will flow from the wind turbines into the fault. Requirements may exist on the maximum or minimum permitted levels.

POWER QUALITY

This term covers several separate issues (IEC, 2008). There are usually limits on the harmonic currents that the wind farm can introduce into the network, and in this area, detailed analysis can be difficult. Ideally the existing background harmonics on the network should be established, but these are often unknown.

Figure II.5.1: Examples of SCADA functions for active power control of wind power plants



On weak networks, voltage steps, caused by wind turbines starting or stopping, or the energisation of transformers, can be a problem. A related problem is voltage flicker, which can be caused by wind turbines starting or stopping, or even when they are in continuous operation.

FUTURE DEVELOPMENTS

As noted above, as wind penetration increases, future technical requirements may well become more onerous.

One possible requirement is for an 'inertia function'. The spinning inertias of a conventional power plant provide considerable benefit to the power system by acting as a flywheel, and thereby reducing the short-term effects of differences in supply and demand. Variable speed wind turbines have no such equivalent effect, but theoretically their control systems could provide a function that mimics the inertia effect.

There may also be a move towards markets for control services, rather than mandatory requirements. This would make sense economically, as the generator best able to provide the service would be contracted. Also, due to the very low marginal cost of renewable energy sources, such as wind energy, it would be more environmentally and economically effective. For example, if a wind farm provided a useful service to the network operator in terms of voltage control (in other words it did more than just make up for its negative effects), then the wind farm could be paid for this service. This may be cheaper than other options available to the network operator.

HARMONISATION OF GRID CODES

The way in which grid code requirements in Europe have developed has resulted in gross inefficiencies and additional costs for consumers, manufacturers and wind farm developers. With the increasing penetration of wind energy, there is an increasing need to develop a harmonised set of grid code requirements. Harmonised technical requirements will maximise efficiency for all parties, and should be employed wherever possible and appropriate. However, it is not practical to completely harmonise technical requirements immediately, since this could lead to the unnecessary implementation of the most stringent requirements from each Member State, which would not be efficient or economically sound.

EWEA has established a Grid Code Working Group among its members. The group consists of wind turbine manufacturers, wind farm operators, service providers, certification bodies and engineering companies. There is a consensus in the industry that there is an urgent need to carry out a harmonisation exercise, as wind penetration is forecast to increase significantly in the short to medium term. The working group is working on a two-step approach:

1. a structural harmonisation exercise, with the aim of establishing a grid code template with common definitions, parameters, units and figures, as well as a common structure; and
2. a technical harmonisation exercise, with the aim of adapting existing grid code parameters to the new grid code template.

This harmonisation strategy will be of particular benefit to:

- manufacturers, who will be required to develop only common hardware and software platforms;
- developers, who will benefit from reduced costs; and
- system operators, especially those who have yet to develop their own grid code requirements for wind power plants.

The technical basis for the requirements will be further developed by TSOs and the wind power industry.

II.6 WIND POWER'S CONTRIBUTION TO SYSTEM ADEQUACY

This chapter discusses the extent to which installed wind power capacity statistically contributes to the guaranteed generation capacity at peak load. This firm capacity part of the installed wind capacity is called 'capacity credit', and is relevant since total wind power capacity will be a substantial fraction of the total generation capacity. At the European level, this will represent 30–40 per cent of total generating capacity, corresponding to the wind power targets for 2020 and 2030. However, in 2008, wind power capacity only represents around 10 per cent of European generation capacity.

Substantial amounts of new capacity need to be built in the coming decades to meet increasing demand in Europe and to replace old plants. UCTE estimates that, by 2015, generating capacity in its area will increase by 90 GW, with 60 GW coming from renewables, the majority of which will be wind power.

As for all renewable sources that cannot be stored, wind has a capacity credit that is lower than that of conventional generation technologies. However, there is a certain amount of firm wind capacity that contributes to the adequacy of the power system. Before expanding on the capacity credit of wind power, a brief explanation will be given of the current methods of estimating power system adequacy.

Security of Supply and System Adequacy

The peak demand (or peak load) of electricity in Europe is constantly increasing. Over the coming years, UCTE expects a rise in peak demand of around 1.6–1.7 per cent per year (compared with 2 per cent up to 2007) (Figure II.6.1). The peak demand is a strategic parameter, since it determines the required generating and transmission capacities. As a matter of convention, for system design purposes, peak load values at specific points during the year – in January and July – are considered.

The way in which the power system can match the evolution in electricity demand is expressed as 'system adequacy'. System adequacy measures the ability of a power system to cope with its load in all the steady states it may operate in under standard conditions. This adequacy has different components:

- the ability of the generation assets to cover the peak load, taking into account uncertainties in the generation availability and load level; and
- the ability of the transmission system to perform, considering the flexibility provided by interconnection and import and export flows.

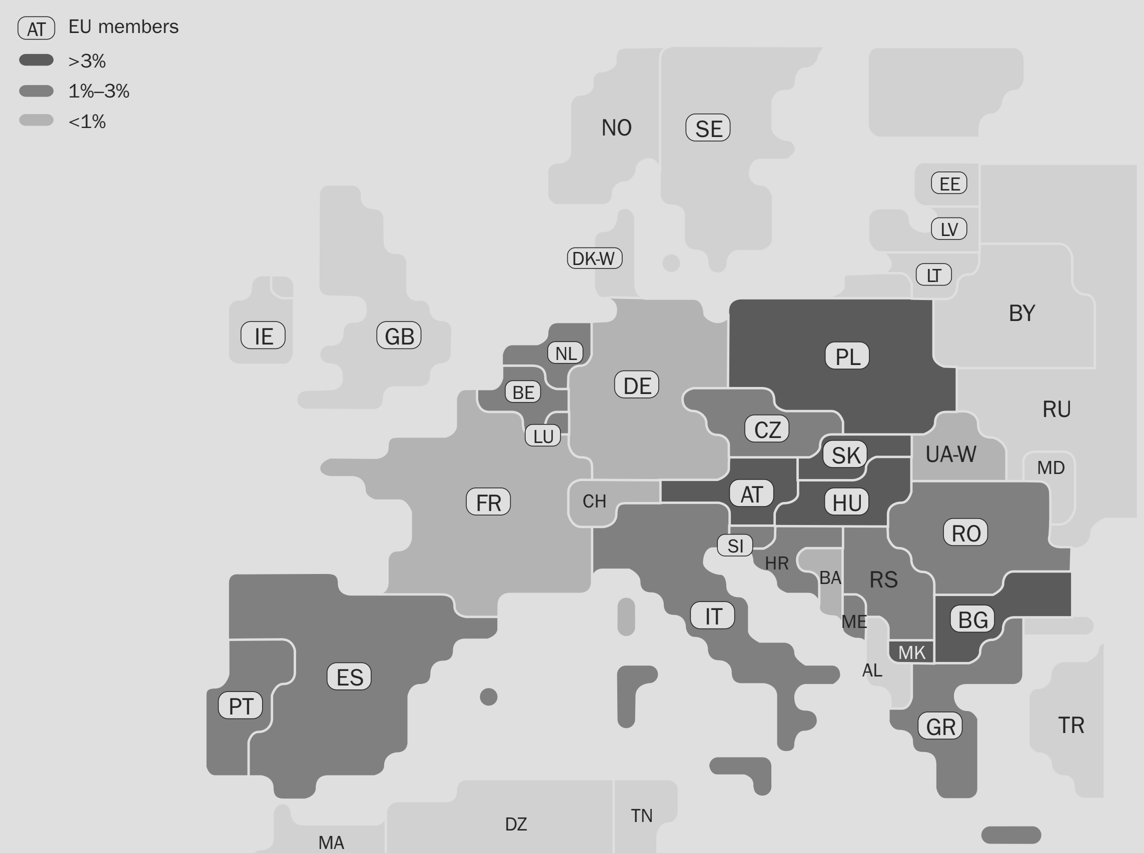
System operators are responsible for maintaining system adequacy at a defined high level. In other words, they should ensure that the generation system is able to cover the peak demand, avoiding loss-of-load events, for a given security of supply. The various national regulations regarding this 'security of supply' range from a 99 per cent security level (in 1 out of 100 years the peak load cannot be covered, such as in Germany) to 91 per cent (1 event in 10 years, such as in the UK).

As the whole European system is interconnected, it is logical for national TSOs to harmonise their approaches towards system adequacy. This is addressed mainly by the larger systems, such as UCTE, the Nordic system, and the British and Irish systems. The assessment methods of generation adequacy can be deterministic or probabilistic, or a combination of both. Even from a national point of view, the system adequacy assessment involves transnational issues. This is because, at the moment of peak load, it may be necessary to have access to power produced by a neighbouring country, so the transmission system should be able to carry and direct these transnational power flows.

The UCTE system's adequacy is being annually reviewed over a period of ten years. Generation adequacy assessment is based on the estimation of 'remaining capacity', which can be interpreted as:

- the capacity needed by the system to cover the difference between the peak load of each country and

Figure II.6.1: Overview of growth in electricity demand in the UCTE area



Source: UCTE (2008)

the load at the UCTE synchronous reference time ('margin against peak load'); or

- exceptional demand variation and unplanned outages that the system operators have to cover with additional reserves.

Generation adequacy assessment underscores how each country could satisfy its interior load with the available national capacity. Transmission adequacy assessment then investigates whether the transmission system is large enough to enable the potential imports and exports resulting from various national power balances, thus improving the reliability of the European power system.

In the Nordel zone, TSOs still conduct these reviews, but theoretically the electricity market price signals are considered sufficient to trigger the building of new capacity to fulfil adequacy needs. As long as the results of the reviews are positive, there is no need to keep reserves in the power system. However, in many countries, a number of contracts are drawn up to ensure that there is spare capacity available in extreme loading situations, often with older plants or loads that can be switched on or off in critical situations.

In the adequacy estimation, each power plant is assigned a typical capacity value. This takes into account scheduled and unscheduled outages. There are no plants with a capacity value of 100 per cent, since there is always the possibility that capacity will not be available when required. In its forecast, UCTE is looking at increasing shares of wind power in the coming years. It is clear from the UCTE system adequacy forecasts that there is not yet a national TSO standard for the determination of wind power's capacity credit.

Capacity Credit of Wind Power

CAPACITY CREDIT IS THE MEASURE FOR FIRM WIND POWER

The contribution of variable output wind power to system security, that is the capacity credit of wind, is estimated by determining the capacity of conventional plants displaced by wind power, whilst maintaining the same degree of system security, in other words an unchanged probability of failure to meet the reliability criteria for the system. Alternatively, it is estimated by determining the additional load that the system can carry when wind power is added, maintaining the same reliability level.

Many national wind integration studies have been giving special attention to the capacity credit of wind, as in some ways it is a 'synthetic' indicator of the potential benefit of wind as a generator in the system. Sometimes the capacity credit of wind power is measured against the outage probabilities of conventional plants.

CAPACITY CREDIT VALUES OF WIND POWER

Despite the variations in wind conditions and system characteristics among the European countries and regions, capacity credit calculations are fairly similar (Giebel, 2005).

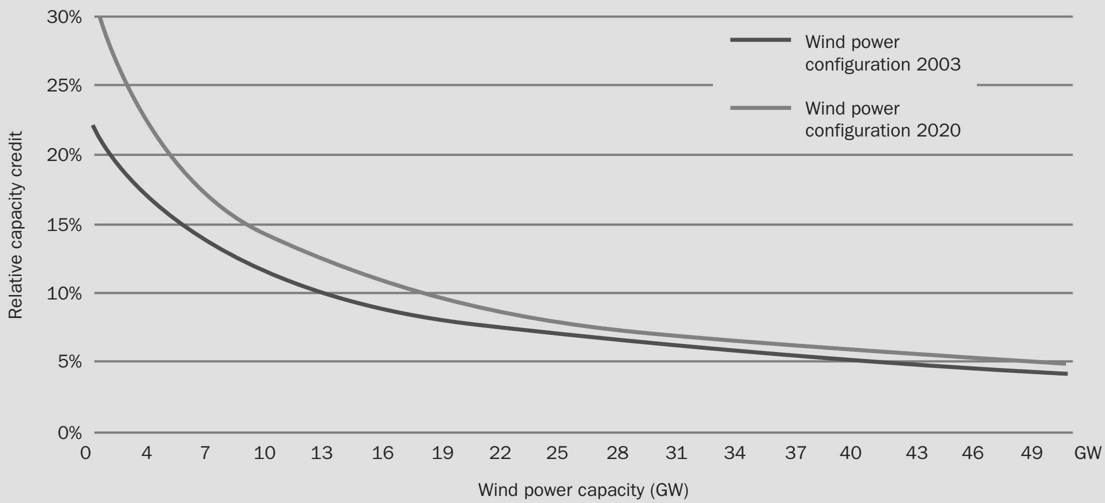
For low wind energy penetrations levels, the relative capacity credit of wind power (that is 'firm' capacity as a fraction of total installed wind power capacity) will be equal or close to the average production (load factor) during the period under consideration, which is usually the time of highest demand. For north European countries, this is at wintertime and the load factor is typically at 25–30 per cent onshore and up to 50 per cent offshore. The load factor determining the capacity credit in general is higher than the average yearly load factor.

With increasing penetration levels of wind energy in the system, its relative capacity credit reduces. However, this does not mean that less conventional capacity can be replaced, but rather that a new wind plant added to a system with high wind power penetration levels will substitute less than the first wind plants in the system. This is illustrated in Figure II.6.2, where the relative capacity credit tails off towards a value depending mainly on the minimum load factor.

Table II.6.1 summarises the factors leading to higher or lower levels of capacity credit. Figure II.6.2, which is based on calculations in the DENA 1 study (DENA, 2005), shows the effect on capacity credit of expected improved load factors in Germany resulting from improved wind power technology (more efficient rotors) and the use of sites with higher wind speeds (offshore).

Wind power thus displaces conventional capacity in the system. The fraction of wind power that displaces conventional capacity may be limited, but the corresponding absolute capacities are significant. The aggregated capacity credit of the wind power plants in a system depends on many factors. Major decisive factors depend on the power system being considered (reliability level and flexibility of the generation mix) and the penetration level of wind power in the system. Other factors are related to wind and wind technology, such as the average capacity factor[9] and the geographical dispersion of wind plants in the system. The relative capacity credit decreases from a value approximately equal to the load factor at high load (25–35 per cent) for

Figure II.6.2: Relationship of installed wind power and capacity credit in Germany



Source: DENA (2005)

Table II.6.1: Factors affecting positively and negatively the value of the capacity credit of a certain amount of wind power in the system

Higher capacity credit (%)	Lower capacity credit (%)
Low penetration of wind power	High penetration of wind
Higher average wind speed; high wind season when demand peaks	Lower average wind speeds
Lower degree of system security	High degree of system security
Higher wind power plant (aggregated) capacity factor or load factor (determined by wind climate, plant efficiency and specific rated power per m^2)	Lower aggregated capacity factor (or load factor) of wind power
Demand and wind are correlated	Demand and wind uncorrelated
Low correlation of wind speeds at the wind farm sites (often related to large size of area considered)	Higher correlation of wind speeds at wind farm sites; smaller areas considered
Good wind power exchange through interconnection	Poor wind power exchange between systems

Source: EWEA

low penetrations to approximately 10–15 per cent at high penetrations.

Although wind power has a capacity credit both physically and technically, this characteristic currently has no value in the power market as wind power producers are not generally rewarded for providing firm capacity in the system.

II.7 ECONOMIC ASPECTS: INTEGRATION COSTS AND BENEFITS

The introduction of significant amounts of wind energy into the power system brings a series of economic impacts, both positive and negative. At power system level, two main factors determine wind energy integration costs:

1. balancing needs; and
2. grid infrastructure.

The additional balancing cost in a power system arises from the inherent variable nature of wind power, requiring changes in the configuration, scheduling and operation of other generators to deal with unpredicted deviations between supply and demand. Here, we demonstrate that there is sufficient evidence available from national studies to make a good estimate of such costs (see page 168). Furthermore, they are fairly low in comparison with the generation costs of wind energy and the overall balancing costs of the power system.

Network upgrade costs are necessary for a number of reasons. First, additional transmission lines and capacity need to be provided to reach and connect existing and future wind farm sites and to transport power flows in the transmission and distribution networks. These flows result both from an increasing demand and trade of electricity and from the rise of wind power. At significant wind energy penetrations, depending on the technical characteristics of the wind projects and trade flows, the networks must also be adapted to improve voltage management. Furthermore, limited interconnection capacity is often a barrier for optimally capturing the benefits of the continental nature of the wind resource, other renewable energy sources and electricity trade in general. In this respect, any infrastructure improvement will provide multiple benefits to the system, and therefore its cost should not be allocated only to wind power generation.

The cost of modifying the power system with significant amounts of wind energy increases in a linear fashion, and identifying its 'economic optimum' is not evident, as costs are accompanied by benefits. From the studies carried out so far, and the extrapolation of their results to high penetration levels, it is clear that the integration of more than 20 per cent of wind power into the EU power system would be economically as well as environmentally beneficial.

Additional Balancing and Network Costs

ADDITIONAL BALANCING COSTS

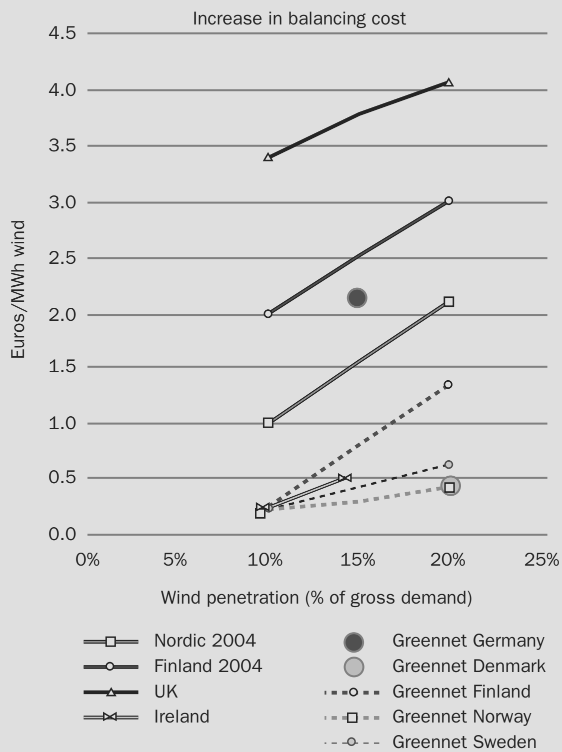
Additional balancing requirements in a system depend on a whole range of factors, including:

- the level of wind power penetration in the system, as well as the characteristic load variations and the pattern of demand compared with wind power variations;
- geographical aspects, such as the size of the balancing area, geographical spread of wind power sites and aggregation;
- the type and marginal costs of reserve plants (such as fossil and hydro);
- costs and characteristics of other mitigating options present in the system, such as storage;
- the possibility of exchanging power with neighbouring countries via interconnectors; and
- the operational routines of the power system, for example how often the forecasts of load and wind energy are updated (gate closure times) and the accuracy, performance and quality of the wind power forecast system used.

At wind energy penetrations of up to 20 per cent of gross demand, system operating cost increases by about €1–4/MWh of wind generation. This is typically 10 per cent or less of the wholesale value of wind energy. Note that these figures refer to balancing costs; costs given earlier (page 168) were for the reserves requirement.

Figure II.7.1 illustrates the costs from several studies as a function of wind power penetration. Balancing

Figure II.7.1: Estimates for the increase in balancing and operating costs due to wind power



Source: Holttinen et al. (2007)[10]

costs increase on a linear basis with wind power penetration; the absolute values are moderate and always less than €4/MWh at 20 per cent level (and more often in the range below €2/MWh).

There are several major contributing factors to lower balancing costs:

- **Larger areas**: Large balancing areas offer the benefits of lower variability. They also help decrease the forecast errors of wind power, and thus reduce the amount of unforeseen imbalance. Large areas favour the pooling of more cost-effective balancing resources. In this respect, the regional aggregation of power markets in Europe is expected to improve the economics of wind energy integration. Additional and better interconnection is the key to enlarging balancing areas. Certainly, improved interconnection will bring benefits for wind power integration, and these are presently quantified by studies such as TradeWind.
- **Reducing gate closure times**: This means operating the power system close to the delivery hour. For example, a re-dispatch, based on a four- to six-hour forecast update, would lower the costs of integrating wind power compared to scheduling based on only day-ahead forecasts. In this respect, the emergence of intraday markets is good news for the wind energy sector.
- **Improving the efficiency of the forecast systems**: Balancing costs could be decreased if the wind forecasts could be improved, leaving only small deviations to the rest of the power system. Experience in different countries (Germany, Spain and Ireland) has shown that the accuracy of the forecast can be improved in several ways, ranging from improvements in meteorological data supply to the use of ensemble predictions and combined forecasting. In this context, the forecast quality is being improved by making a balanced combination of different data sources and methods in the prediction process.

ADDITIONAL NETWORK COSTS

The consequences of adding more wind power into the grid have been analysed in several European countries (see, for example, Holttinen et al., 2007) (Table II.7.1). The national studies quantify grid extension measures and the associated costs caused by additional generation and demand in general, and by wind power production in particular. The analyses are based on load flow simulations of the corresponding national transmission and distribution grids and take into account different scenarios for wind energy integration using existing, planned and future sites.

It appears that additional grid extension/reinforcement costs are in the range of €0.1–5/MWh wind,

Table II.7.1: Grid upgrade costs from selected national system studies

Country	Grid upgrade costs, €/kW	Installed wind power capacity, GW	Remarks
Portugal	53–100	5.1	Only additional costs for wind power
The Netherlands	60–110	6.0	Specifically offshore wind
UK	45–100	8.0	
UK	62–85	26.0	20% wind power penetration
Germany	100	36.0	DENA 1 study

Source: Holttinen et al. (2007)

typically around 10 per cent of wind energy generation costs for a 30 per cent wind energy share. As for the additional balancing costs, the network cost increases with the wind penetration level. Grid infrastructure costs (per MWh of wind energy) appear to be around the same level as additional balancing costs for reserves in the system to accommodate wind power.

The costs of grid reinforcement due to wind energy cannot be directly compared, as circumstances vary significantly from country to country. These figures also tend to exclude the costs for improving interconnection between Member States. This subject is now being investigated by the TradeWind project (www.trade-wind.eu/), which investigates scenarios up to 2030.

Allocating Grid Infrastructure Costs

There is no doubt that the transmission and distribution infrastructure will have to be extended and reinforced in most EU countries when large amounts of wind power are connected. However, these adaptations are necessary not only to accommodate wind power, but also to connect other electricity sources to meet the rapidly growing European electricity demand and trade flows.

However, the present grid system is not used to its full capacity and present standards and practices of transmission lines by TSOs are still largely based on the situation before wind energy came into the picture. As wind power is producing in a whole range of partial load states, wind farms will only utilise the full rated power transmission capacity for a fraction of the time. In some cases, where there is adjustable power production (such as hydropower with reservoir), the combination of wind and hydro can use the same transmission line.

The need to extend and reinforce the existing grid infrastructure is also critical. Changes in generation and load at one point in the grid can cause changes throughout the system, which may lead to power congestion. It is not possible to identify one (new) point of generation as the single cause of such difficulties, other than it being 'the straw that broke the camel's back'. Therefore, the allocation of costs required to accommodate a single new generation plant to one plant only (for example a new wind farm) should be avoided.

In the context of a strategic EU-wide policy for long-term, large-scale grid integration, the fundamental ownership unbundling between generation and transmission is indispensable. A proper definition of the interfaces between the wind power plant itself (including the 'internal grid' and the corresponding electrical equipment) and the 'external' grid infrastructure (new grid connection and extension/reinforcement of the existing grid) needs to be discussed, especially for remote wind farms and offshore wind energy. This does not necessarily mean that the additional grid tariff components, due to wind power connection and grid extension/reinforcement, must be paid by the local/regional customers only. These costs could be socialised within a 'grid infrastructure' component at national or even EU level. Of course, appropriate accounting rules would need to be established for grid operators.

Future System Cost Developments

Assessment of the way in which integration costs beyond the present 'low to moderate' penetration level will increase depends on how the future evolution of the power system is viewed. A 'static power system' assumption becomes less plausible with increasing wind penetration, as wind serving a substantial (higher than 25 per cent) fraction of the demand will cause the system to evolve over time. Furthermore, the generation mix is likely to change significantly during this long period of wind development. For example, it is predicted that gas power generation will increase dramatically (depending on fuel costs), which will make the power system more flexible. Hence the integration costs of wind energy increase smoothly and proportionally as penetration levels increase.

Costs beyond penetration levels of about 25 per cent will depend on how the underlying system architecture changes over time, as the amount of installed wind gradually increases, together with other generating technologies. For example, in order to accommodate high amounts of wind power, a system with a generation mix dominated by fast-ramping gas turbines or hydro is much more flexible than a system dominated by nuclear or coal, as it can respond quickly to changes in supply and demand.

Up to a penetration level of 25 per cent, the integration costs have been analysed in detail and are consistently low. The economic impacts and integration issues are very much dependent on the power system in question. Important factors include:

- the structure of the generation mix and its flexibility;
- the strength of the grid;
- the demand pattern;
- power market mechanisms; and
- structural and organisational aspects.

Technically, methods that have been used by power engineers for decades can be applied for integrating wind power. But for large-scale integration (penetration levels typically higher than 25 per cent), new power system concepts may be necessary, and it would be sensible to start considering such concepts immediately. Practical experience with large-scale integration in a few regions demonstrates that this is not merely a theoretical discussion. The feasibility of large-scale penetration has already been proved in areas where wind power currently meets 20, 30 and even 40 per cent of consumption (Denmark and regions of Germany and Spain).

Wind Power will Reduce Future European Power Prices

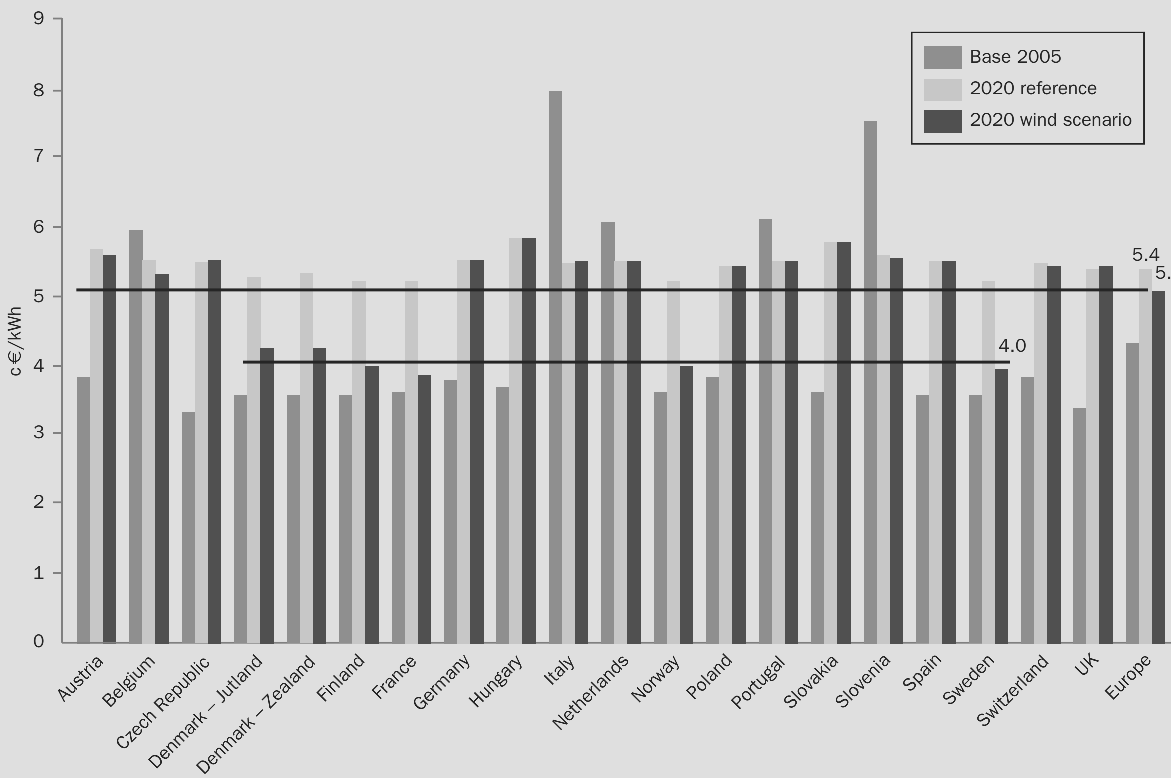
In a 2008 study (Skytte, 2008), Econ-Pöyry used its elaborate power model to investigate the electricity price effects of increasing wind power in Europe to 13 per cent in 2020.

In a business-as-usual scenario, it is assumed that the internal power market and additional investments in conventional power will more or less levelise the power prices across Europe up until 2020 (reference scenario). However, in a large-scale wind scenario (wind covering 13 per cent of EU electricity consumption) this might not be the case.

In areas where power demand is not expected to increase very much and in areas where the amount of new deployment of wind energy is larger than the increase in power demand, wind energy will substitute the most expensive power plants. This will lower the price levels in these areas, the study shows.

In the EU, the expected price level is around 5.4c€/kWh on average in 2020 for the reference case (Figure II.7.2) with a slightly higher price on the continent than in the Nordic countries, but with smaller price differences than today.

Figure II.7.2: Price levels in 2005 and in the 2020 reference and wind scenarios



Source: Econ-Pöyry

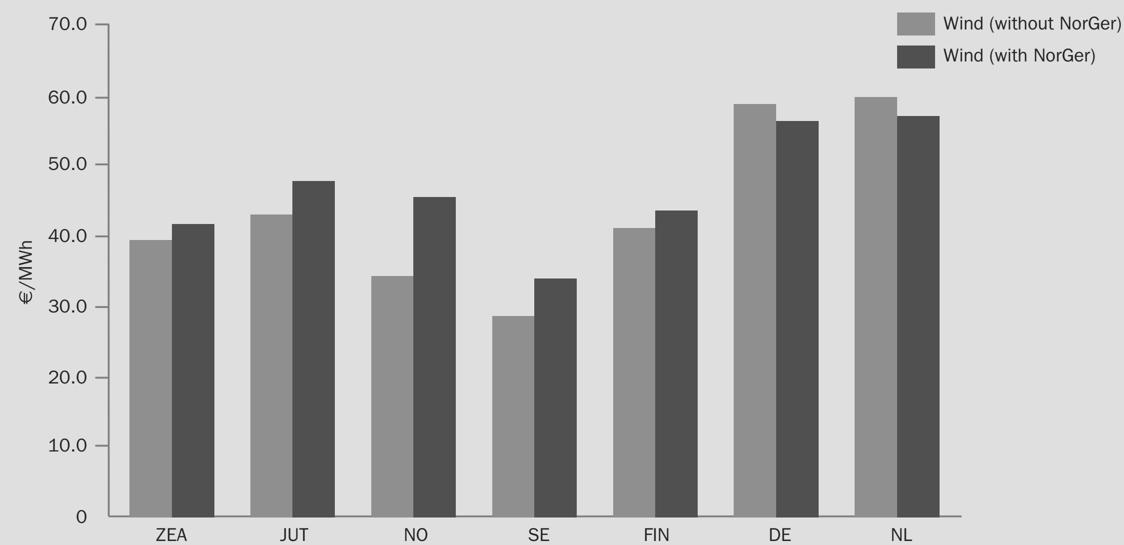
In the wind scenario, the average price level in the EU decreases from 5.4 to 5.1c€/kWh compared to the reference scenario. However, the effects on power prices are different in the hydropower-dominated Nordic countries than in the thermal-based countries on the European continent.

In the wind scenario, wind energy reduces power prices to around 4c€/kWh in the Nordic countries. Prices in Germany and the UK remain at the higher level. In other words, a larger amount of wind power would create larger price differences between the (hydro-dominated) Nordic countries and the European continent.

One implication of price decreases in the Nordic countries is that conventional power production becomes less profitable. For large-scale hydropower the general water value decreases. In Norway, hydropower counts for the major part of the power production. However, large-scale implementation of wind creates a demand for flexible production that can deliver balancing services – opening up a window of opportunities for flexible production such as hydropower.

With large amounts of wind in the system, there will be an increased need for interconnection. This is also confirmed by the fact that, in the Econ-Pöyry model runs, with 13 per cent wind in the system compared to the reference scenario, the congestion rent (i.e. the cable income) increases on most transmission lines. This is also something one would expect: with more

Figure II.7.3: Average prices in the wind scenario – with and without the NorGer cable



volatility in the system, there is a need for further interconnection in order to be better able to balance the system.

In order to simulate the effect of further interconnection, the same model runs were repeated, i.e. the wind and the reference scenario, but this time with a 1000 MW interconnector between Norway and Germany in place, the so-called 'NorGer cable'.[11] When running the wind scenario, Econ-Pöyry found that the congestion rent on such a cable would be around €160 million in the year 2020 in the reference scenario, while it would be around €200 million in the wind scenario.

With the cable in place it should first be observed that such a cable would have a significant effect on the average prices in the system, not only in Norway and Germany, but also in the other countries in the model. This is illustrated by Figure II.7.3. In the Nordic area the average prices are increased – the Nordic countries would import the higher prices in northern continental Europe – while in Germany (and The Netherlands) they are decreased. This is because, in the high-price peak hours, power is flowing from Norway to Germany. This reduces the peak prices in Germany, while it increases the water values in Norway. In the off-peak low-price hours, the flow reverses, with Germany exporting to Norway in those hours where prices in Germany are very low. This increases off-peak prices in Germany and decreases water values. However, the overall effect, compared to the situation without a cable, is higher prices in Norway and lower prices in Germany. Although such effects are to be expected, this does not always have to be the case. In other cable analysis projects, Econ-Pöyry found that an interconnector between a thermal high-price area and a hydro low-price area may well reduce prices in both areas.

Concluding Remarks

Experience and studies provide positive evidence on the feasibility and solutions for integrating the expected wind power capacity in Europe for 2020, 2030 and beyond. Today, the immediate questions concern how to address a number of issues in the most cost-effective manner.

There is now a clearer understanding regarding the behaviour of aggregated wind plants at the power system level, as well as how system costs evolve with increasing wind energy penetration. In the range of expected wind energy penetration levels for the coming decades, the cost increments for additional reserves in the system, to deal with increased variability, remain moderate. Additional impacts that wind power may impose on the system, due to its variability and limited predictability, should be reduced by:

- making use of geographical aggregation;
- improved control of wind plants at both local and system levels;
- using state-of-the-art forecasting, monitoring and communication techniques; and
- reinforcing network.

Specific grid code requirements are now being imposed for wind farms, taking into account the continuous development of wind power plant capabilities. In this respect, a more proactive involvement of the wind power industry in the development of harmonised grid code requirements in Europe is essential.

A substantial upgrade of transmission networks is required, and the creation of a transnational offshore grid would bring additional benefits. This network development goes hand-in-hand with the necessary upgrades to achieve a more efficient European Internal Electricity Market and improved competition in European power markets. In this respect, a definite challenge is the creation of appropriate market rules, including incentives to make power generation and transmission evolve in a direction that facilitates variable output and decentralised generation, by increasing flexibility and providing additional network capacity, not only within the national grids, but also at the transnational level.

There is also a need for studies at the European level to provide a technical and scientific basis for grid upgrades and market organisation.

Part II Notes

1 Instead of shutting down the wind turbine above cut-out, the power curve above cut-out wind speed (25 m/s) decreases gradually to reach zero power at 35 m/s.

2 See www.trade-wind.eu.

3 Except for unplanned outages of conventional plants, which by nature are not predictable. In this respect, wind power has an advantage, due to its modular nature and the low levels of capacity that are lost at one time during outages.

4 The error reduction in the graph is defined as the ratio between the RMSE (root-mean-square-error) of regional prediction and the RMSE of a single site, based on the results of measured power production at 40 wind farms in Germany.

5 The effect of the additional balancing costs at consumer level should take into account the benefits of wind power. Several studies show that the overall effect (resulting from costs and benefits) of integrating wind power is to reduce the price of electricity to the consumer.

6 FACTS (Flexible AC Transmission Systems): power electronic devices locally implemented in the network, such as STATCOMs and static VAR compensators (SVCs).

7 The MVAR capability is the capability to control reactive power by generation or controlled consumption.

8 FRT is the ability for generators to remain stable and connected to the network when faults occur in the transmission network.

9 Capacity factor depends on the relationship between rotor size and generator rating.

10 The currency conversion used in this figure is EUR1 = GBP0.7 = US$1.3. For the UK 2007 study, the average cost is presented; the range for 20 per cent penetration level is from €2.6–4.7/MWh.

11 Classic model runs were repeated with a NorGer cable in place, in order to obtain investment figures for 2020, and to be consistent in methodology and approach. It should be noted that the NorGer cable does not have too pronounced an effect on investment levels. The size of the cable has not yet been decided, but a 1000 MW cable is probably a fair estimate and sufficient in order to simulate the effects of further interconnections.