

**Powering Europe:**

**wind energy and the electricity grid**

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# Introduction: a European vision

## Introduction

In order to achieve EU renewable energy and CO2 emission reduction targets, significant amounts of wind energy need to be integrated into Europe’s electricity system. This report will analyse the technical, economic and regulatory issues that need to be addressed in order to do so through a review of the available literature, and examine how Europe can move towards a more secure energy future through increased wind power production.

The report’s main conclusions are that the capacity of the European power systems to absorb significant amounts of wind power is determined more by economics and regulatory frameworks than by technical or practical constraints. Larger scale penetration of wind power faces barriers not because of the wind’s variability, but because of inadequate infrastructure and interconnection coupled with electricity markets where competition is neither effective nor fair, with new technologies threatening traditional ways of thinking and doing. Already today, it is generally considered that wind energy can meet up to 20 % of electricity demand on a large electricity network without posing any serious technical or practical problems.

When wind power penetration levels are low, grid operation will not be affected to any significant extent. Today wind power supplies more than 5 % of overall EU electricity demand, but there are large regional and national differences. The control methods and backup available for dealing with variable demand and supply that are already in place are more than adequate for dealing with wind power supplying up to 20 % of electricity demand, depending on the specific system and geographical distribution. For higher penetration levels, changes may be needed in power systems and the way they are operated to accommodate more wind energy.

Experience with wind power in areas of Spain, Denmark, and Germany that have large amounts of wind energy in the system, shows that the question as to whether there is a potential upper limit for renewable penetration into the existing grids will be an economic and regulatory issue, rather than a technical one.

For those areas of Europe where wind power development is still in its initial stages, many lessons can be learned from countries with growing experience, as outlined in this report. However, it is important that stakeholders, policy makers and regulators in emerging markets realize that the issues that TSOs in Spain, Denmark and Germany are faced with will not become a problem for them until much larger amounts of wind power are connected to their national grids.

The issues related to wind power and grid integration mentioned in this report are based on a detailed overview of best practices, past experiences, descriptions and references to technical and economic assessments.

The report collects and presents detailed facts and results, published in specialized literature, as well as contributions from experts and actors in the sector. The aim is to provide a useful framework for the current debates on integrating wind power into the grid.

## Turning the energy challenge into a competitive advantage

Europe is importing 54 % of its energy (2006), and that share is likely to increase substantially in the next two decades unless a major shift occurs in Europe’s supply strategy. Most of Europe’s oil comes from the Middle East and the larger share of its gas from just three countries: Russia, Algeria and Norway.

The European economy relies on the availability of hydrocarbons at affordable prices. Europe is running out of indigenous fossil fuels at a time when fossil fuel prices are high, as is the volatility of those prices.

The combination of high prices and high volatility pressures the energy markets, and increases the risk on energy investments, thus driving up energy prices including electricity prices. The continued economic and social progress of Europe will depend on its ability to decarbonise its energy mix in order to mitigate the risk to the climate, and use its indigenous renewable resources to mitigate the risk to its energy supply. Without reliable, sustainable, and reasonably priced energy there can be no sustainable long term growth.

It is essential that Europe develops its own internal energy resources as far as possible, and that it strongly promotes energy efficiency. Europe has always led the way in renewable energy capacity development, particularly due to the implementation of directives 2001/77/EC and 2009/28/EC for the promotion of the use of renewable energy sources in the European energy mix.

Europe has a particular competitive advantage in wind power technology. Wind energy is not only able to contribute to securing European energy independence and climate goals in the future, it could also turn a serious energy supply problem into an opportunity for Europe in the form of commercial benefits, technology research, exports and employment.

The fact that the wind power source is free and clean is economically and environmentally significant, but just as crucial is the fact that the cost of electricity from the wind is fixed once the wind farm has been built. This means that the economic future of Europe can be planned on the basis of known, predictable electricity costs derived from an indigenous energy source free of the security, political, economic and environmental disadvantages associated with conventional technologies.

## Wind power and European electricity

Due to its ageing infrastructure and constant demand growth, massive investment in generation plant and grids are required. Over the next 12 years, 360 GW of new electricity capacity (50 % of current EU electricity generating capacity) needs to be built to replace ageing power plants to meet the expected increase in demand. Since energy investments are long-term investments, today’s decisions will influence the energy mix for the next decades. The vision presented in this document shows that wind power meets all the requirements of current EU energy policy and simultaneously offers a way forward in an era of higher fuel and carbon prices.

Wind energy technology has made major progress since the industry started taking off in the early 1980s. Thirty years of technological development means that today’s wind turbines are a state-of-the-art modern technology: modular and quick to install. At a given site, a single modern wind turbine annually produces 200 times more electricity and at less than half the cost per kWh than its equivalent twenty five years ago.

The wind power sector includes some of the world’s largest energy companies. Modern wind farms deliver grid support services – for example voltage regulation – like other power plants do. Effective regulatory and policy frameworks have been developed and implemented, and Europe continues to be the world leader in wind energy.

Wind currently provides more than 5 % of Europe’s electricity , but as the cheapest of the renewable electricity technologies, onshore wind will be the largest contributor to meeting the 34 % share of renewable electricity needed by 2020 in the EU, as envisaged by the EU’s 2009/28 Renewable Energy Directive.

EWEA’s "Baseline" scenario for 2020 requires installed capacity to increase from 80 GW today to 230 GW in 2020. Wind energy production would increase from 163 TWh (2009) to 580 TWh (2020) and wind energy’s share of total electricity demand would increase from 4.2 % in 2009 to 14.2 % in 2020. EWEA’s ”High” scenario requires installed capacity to increase from 80 GW today to 265 GW in 2020. Wind energy production would increase from 163 TWh (2009) to 681 TWh (2020) and wind energy’s share of total electricity demand would increase from 4.2 % in 2009 to 16.7 % in 2020.

On 7 October 2009, the European Commission published its Communication on Investing in the Development of Low Carbon Technologies (SET-Plan) stating that wind power would be "capable of contributing up to 20 % of EU electricity by 2020 and as much as 33 % by 2030" were the industry’s needs fully met. EWEA agrees with the Commission’s assessment. With additional research efforts, and crucially, significant progress in building the necessary grid infrastructure over the next ten years, wind energy could meet one fifth of the EU’s electricity demand in 2020, one third in 2030, and half by 2050.

Meeting the European Commission’s ambitions for wind energy would require meeting EWEA’s high scenario of 265 GW of wind power capacity, including 55 GW of offshore wind by 2020. The Commission’s 2030 target of 33 % of EU power from wind energy can be reached by meeting EWEA’s 2030 installed capacity target of 400 GW wind power, 150 GW of which would be offshore. Up to 2050 a total of 600 GW of wind energy capacity would be envisaged, 250 GW would be onshore and 350 GW offshore. Assuming a total electricity demand of 4000 TWh in 2050 this amount of installed wind power could produce about 2000 TWh and hence meet 50 % of the EU’s electricity demand.

In June 2010 the European Commission’s Joint Research Centre highlighted that provisional Eurostat data showed that in "2009 about 19.9 % (608 TWh) of the total net Electricity Generation (3,042 TWh) came from Renewable Energy sources. Hydro power contributed the largest share with 11.6 %, followed by wind with 4.2 %, biomass with 3.5 % and solar with 0.4 %." It went on to conclude "that if the current growth rates of the above-mentioned Renewable Electricity Generation Sources can be maintained, up to 1,600 TWh (45 – 50 %) of renewable electricity could be generated in 2020."

Whilst the technology has been proven, the full potential of wind power is still to be tapped. Europe’s grid infrastructure was built in the last century with large centralized coal, hydro, nuclear and, more recently, gas fired power plants in mind. The future high penetration levels of wind and other renewable electricity in the power system require decision makers and stakeholders in the electricity sector to work together to make the necessary changes to the grid infrastructure in Europe.

By 2020, most of the EU’s renewable electricity will be produced by onshore wind farms. Europe must, however, also use the coming decade to exploit its largest indigenous resource, offshore wind power. For this to happen in the most economical way Europe’s electricity grid needs major investments, with a new, modern offshore grid and major grid reinforcements on land.

The current legal framework, with newly established bodies ENTSO-E and ACER, the key deliverable of the 10-Year Network Development Plan, as well as the ongoing intergovernmental "North Seas Countries’ Offshore Grid Initiative" are all steps in the right direction and the political momentum for grid development and the integration of renewable energy is evident.

## Wind power in the system

Wind cannot be analyzed in isolation from the other parts of the electricity system, and all systems differ. The size and the inherent flexibility of the power system are crucial for determining whether the system can accommodate a large amount of wind power. The role of a variable power source like wind energy needs to be considered as one aspect of a variable supply and demand in the electricity system.

Grid operators do not have to take action every time an individual consumer changes his or her consumption, for example, when a factory starts operation in the morning. Likewise, they do not have to deal with the output variation of a single wind turbine. It is the net output of all wind turbines on the system or large groups of wind farms that matters. Therefore, wind power has to be considered relatively to the overall demand variability and the variability and intermittency of other power generators.

The variability of the wind energy resource should only be considered in the context of the power system, rather than in the context of an individual wind farm or turbine. The wind does not blow continuously, yet there is little overall impact if the wind stops blowing in one particular place, as it will always be blowing somewhere else. Thus, wind can be harnessed to provide reliable electricity even though the wind is not available 100 % of the time at one particular site. In terms of overall power supply it is largely unimportant what happens when the wind stops blowing at a single wind turbine or wind farm site.

## All power sources are fallible

Because the wind resource is variable, this is sometimes used to argue that wind energy per se is not reliable. No power station or supply type is totally reliable – all system assets could fail at some point. In fact, large power stations that go off-line do so instantaneously, whether by accident, by nature or by planned shutdowns, causing loss of power and an immediate contingency requirement. For thermal generating plants, the loss due to unplanned outages represents on average 6 % of their energy generation. When a fossil or nuclear power plant trips off the system unexpectedly, it happens instantly and with capacities of up to 1,000 MW. Power systems have always had to deal with these sudden output variations as well as variable demand. The procedures put in place to tackle these issues can be applied to deal with variations in wind power production as well, and indeed, they already are used for this in some countries.

By contrast, wind energy does not suddenly trip off the system. Variations in wind energy are smoother, because there are hundreds or thousands of units rather than a few large power stations, making it easier for the system operator to predict and manage changes in supply as they appear within the overall system. The system will not notice when a 2 MW wind turbine shuts down. It will have to respond to the shut-down of a 500 MW coal fired plant or a 1,000 MW nuclear plant instantly.

Wind power is sometimes incorrectly described as an intermittent energy source. This terminology is misleading, because on a power system level, intermittent means starting and stopping at irregular intervals, which wind power does not do. Wind is a technology of variable output. It is sometimes incorrectly expressed that wind energy is inherently unreliable because it is variable.

Electricity systems – supply and demand - are inherently highly variable, and supply and demand are influenced by a large number of planned and unplanned factors. The changing weather makes millions of people switch on and off heating or lighting. Millions of people in Europe switch on and off equipment that demands instant power - lights, TVs, computers.

Power stations, equipment and transmission lines break down on an irregular basis, or are affected by extremes of weather such as drought. Trees fall on power lines, or the lines become iced up and cause sudden interruptions of supply. The system operators need to balance out planned and unplanned changes with a constantly changing supply and demand in order to maintain the system’s integrity. Variability in electricity is nothing new; it has been a feature of the system since its inception.

Both electricity supply and demand are variable. The issue, therefore, is not the variability or intermittency per se, but how to predict, manage and ameliorate variability and what tools can be utilized to improve efficiency. Wind power is variable in output but the variability can be predicted to a great extent. This does not mean that variability has no effect on system operation. It does, especially in systems where wind power meets a large share of the electricity demand.

## Main challenges and issues of integration

The levels of wind power connected to certain national electricity systems show that wind power can achieve levels of penetration similar to those of conventional power sources without changes to the electricity system in question. In mid 2010, 80 GW of wind power were already installed in Europe, and areas of high, medium and low penetration levels can be studied to see what bottlenecks and challenges occur. Largescale integration of both onshore and offshore wind creates challenges for the various stakeholders involved throughout the whole process from generation, through transmission and distribution, to power trading and consumers.

In order to integrate wind power successfully, a number of issues have to be addressed in the following areas:

* System design and operation (reserve capacities and balance management, short-term forecasting of wind power, demand-side management, storage, contribution of wind power to system adequacy)
* Grid connection of wind power (grid codes and power quality)
* Network infrastructure issues (congestion management, extensions and reinforcements, specific issues of offshore, interconnection, smart grids)
* Electricity market design issues to facilitate wind power integration (power market rules)

Related to each of these areas are technical and institutional challenges. This report attempts to address both of these dimensions in a balanced way.

## Integration of wind power in Europe: the facts

The contribution from wind energy to power generation as foreseen by EWEA for 2020 (meeting 14-17 % of the EU’s power demand) and 2030 (26-34.7 %) is technically and economically possible, and will bring wind power up to the level of, or exceeding, contributions from conventional generation types. These large shares can be realized while maintaining a high degree of system security, and at moderate additional system costs. However the power systems, and their methods of operation, will need to be redesigned to achieve these goals. The constraints of increasing wind power penetration are not linked to the wind energy technology, but are connected to electricity infrastructure cost allocation, regulatory, legal, structural inefficiencies and market changes, and are part of a paradigm shift in power market organization.

The major issues surrounding wind power integration are related to changed approaches in design and operation of the power system, connection requirements for wind power plants to maintain a stable and reliable supply, and extension and upgrade of the electrical transmission and distribution network infrastructure.

Equally, institutional and power market barriers to increased wind power penetration need to be addressed and overcome.

## Wind plants: the essentials

State-of-the-art wind power technology with advanced control features is designed to enhance grid performance by providing ancillary services. Using these power plant characteristics to their full potential with a minimum of curtailment of wind power is essential for efficiently integrating high levels of wind power. Advanced grid-friendly wind plants can provide voltage control, active power control and fault-ride-through capability. Emulating system inertia will become possible too. The economic value of these properties in the system should be reflected in the pricing in proportion to their cost.

Wind power provides variable generation with predictable variability that extends over different time scales (seconds, minutes, hours and seasons) relevant for system planning and scheduling. The intra-hour variations are relevant for regulating reserves; the hour by hour variations are relevant for load following reserves. Very fast fluctuations on second to minute scale visible at wind turbine level disappear when aggregated over wind farms and regions. The remaining variability is significantly reduced by aggregating wind power over geographically dispersed sites and large areas. Electricity networks provide the key to reduction of variability by enabling aggregation of wind plant output from dispersed locations. Wind plant control can help control variability on a short time scale.

The latest methods for wind power forecasting help to predict the variations in the time scale relevant for system operation with quantifiable accuracy. Aggregating wind power over large areas and dispersed sites and using combined predictions helps to bring down the wind power forecast error to manageable levels in the time frames relevant for system operation (four to 24 hours ahead). Well interconnected electricity networks have many other advantages. In order to control the possible large incidental forecast errors, reserve scheduling should be carried out in time frames that are as short as possible (short gateclosure times), assisted by real time data on wind power production and site specific wind conditions.

The significant economic benefits of improved accuracy justify investment in large meteorological observational networks. The way grid code requirements in Europe have been developed historically has resulted in gross inefficiencies for manufacturers and developers. Harmonized technical requirements will maximize efficiency for all parties and should be employed wherever possible and appropriate. However, it must be noted that it is not practical to completely harmonize technical requirements straight away. In an extreme case this could lead to the implementation of the most stringent requirements from each Member State. This would not be desirable, economically sound, or efficient.

A specific European wind power connection code should be established within the framework of a binding network code on grid connection, as foreseen in the Third Liberalization Package. The technical basis for connection requirements should continuously be developed in work carried out jointly between TSOs and the wind power industry.

EWEA proposes a two step harmonization approach for grid codes: a structural harmonization followed by a technical harmonization. The proposed harmonizing strategies are urgently needed in view of the significant increase in foreseen wind power penetration and should be of particular benefit to:

* Manufacturers, who will now be required only to develop common hardware and software platforms
* Developers, who will benefit from the reduced costs
* System operators, especially those who have yet to develop their own grid code requirements for wind powered plants

The technical basis for the requirements should be further developed in work carried out jointly between TSOs and the wind power industry. If the proposals can be introduced at European level by means of a concise network code on grid connection, it will set a strong precedent for the rest of the world.

## Power system operations with large amounts of wind power

For power systems to increase their levels of wind penetration, all possible measures to increase flexibility in the system must be considered (flexible generation, demand side response, power exchange through interconnection and energy storage) as well as an appropriate use of the active power control possibilities of wind plants. Wind plant power output control can help manage variability for short amounts of time when it is necessary for system security and when economically justified. For the penetration levels expected up to 2020 there is no economic justification in building alternative large scale storage, although additional storage capacity might be required after 2020.

System operators should make adequate use of shortterm wind power forecasting in combination with short gate closure times wherever possible to reduce the need for additional reserve capacity at higher wind power penetration levels. Such reserve capacity will be required to deal with the increased hour ahead uncertainty (load following reserves). Existing conventional plants can often provide this capacity, if they are scheduled and operated in a different way. In addition to using the existing plants – including the slow ramping plants - in a more flexible way, more flexible generation (for example OCGT, CCGT and hydropower) should be favoured when planning the replacement of ageing plants and considering the future generation mix, in order to enable the integration of large-scale variable generation.

Providing better access to flexible reserves situated in neighbouring control areas through interconnectors is also a way of improving the system’s flexibility.

It is crucial that methods of incorporating wind power forecast uncertainties into existing planning tools and models are developed. The significant economic benefits of improved accuracy justify investment in large wind observation networks. Additional R&D efforts are needed to develop these methods and to improve the meteorological data input for forecasting.

The latest studies indicate that 1-15 % of reserve capacity is required at a penetration level of 10 %, and 4-18 % at a penetration level of 20 %. These figures are based on existing examples of high wind power penetration levels (e.g. Spain, Denmark, Germany, Ireland) and a range of system studies (including EWIS), and provide an insight into the additional reserves required for integrating the shares of wind power foreseen for 2020. The large range in the numbers shows that many factors are at play, one of the most important aspects is the efficient use of forecasting tools.

The additional balancing costs at 20 % wind power penetration are in the range of € 2-4/MWh of wind power, mainly due to increased use of fuel reserves. The available system studies show that there is no steep change in reserve requirements, or on deployment costs, with increasing penetration. An efficient integration of large scale wind power (20 % and up) is feasible when the power system is developed gradually in an evolutionary way.

Forecasting error can be mitigated by aggregating plants over wider areas. Aggregating wind power over European transmission networks joins up large areas and dispersed sites, and with the help of combined predictions, it can make wind power forecast error manageable for system operation (forecasts made four-24 hours ahead). Efficient integration of wind power implies installing forecasting tools in the control rooms of the system operators. The cost-benefit ratio of applying centralized forecast systems is very high because of the large reductions in the operational costs (balancing) of power generation brought about by reduced uncertainty. Forecasting needs to be customized to optimize the use of the system reserves at various different time scales of system operation.

A way forward would be to incorporate wind power prediction uncertainties into existing planning tools and models. Intensive R&D is needed in this area.

Clustering wind farms into virtual power plants increases the controllability of the aggregated wind power for optimal power system operation. Practical examples, such as in Spain, demonstrate that operating distributed variable generation sources in a coordinated way improves the management of variability and enhances predictability.

A large geographical spread of wind power on a system should be encouraged through spatial planning, adequate payment mechanisms, and the establishment of the required interconnection infrastructure. This will reduce variability, increase predictability and decrease or remove instances of nearly zero or peak output.

Wind power capacity replaces conventional generation capacity in Europe. The capacity credit of large-scale wind power at European level is in the order of 10 % of rated capacity at the wind power penetrations foreseen for 2020. Aggregating wind power from dispersed sites using and improving the interconnected network increases its capacity credit at European level.

A harmonized method for wind power capacity credit assessment in European generation adequacy forecast and planning is required, in order to properly value the contribution of wind power to system adequacy.

This method would also constitute a basis for valuating wind power capacity in the future liberalized electricity market.

## Upgrading electricity networks: challenges and solutions

In a scenario with substantial amounts of wind power, the additional costs of wind power (higher installed costs, increased balancing, and network upgrade) could be outweighed by the benefits, depending on the cost of conventional fossil fuels. The expected continuing decrease in wind power generation costs is an important factor. The economic benefits of wind become larger when the social, health and environmental benefits of CO2 emission reductions are taken into account.

A truly European grid network would also not only overcome the present congestions on some of the main transmission lines but would also bring about savings in balancing and system operation costs and enabling a functioning internal electricity market.

Financing schemes for pan-European transmission grid reinforcements should be developed at EU level, as well as harmonized planning (including spatial planning) and authorization processes. The revised TEN-E Instrument in the form of a new "EU Energy Security and Infrastructure Instrument" should be better funded and become functional and effective in adding crucial new interconnectors.

With the increased legal separation between generators and network owners/operators, as stipulated in the EU’s Third Liberalization Package (2009/72/EC), the technical requirements which govern the relationship between them must be clearly defined. The introduction of variable renewable generation has often complicated this process significantly, as its generation characteristics differ from the directly-connected synchronous generators used in large conventional power plants.

Upgrading the European network infrastructure at transmission and distribution level is vital for the emerging single electricity market in Europe, and is a fundamental step on the way to the large-scale integration of wind power. Better interconnected networks help aggregating dispersed (uncorrelated) generation leading to continental smoothing, improving the forecasting ability, and increasing the capacity credit of wind power.

For its 2030 wind and transmission scenario (279.6 GW of installed wind capacity), the TradeWind study estimates a yearly reduction of € 1,500 million in the total operational costs of power generation as a result of interconnection upgrades. European studies like TradeWind and EWIS have quantified the huge benefits of increasing interconnection capacities for all grid users, and have identified specific transmission corridors to facilitate the implementation of large-scale wind power in Europe.

The costs of upgrading of the European network should be socialized. Grid connection charges should be fair and transparent and competition should be encouraged.

Major national studies in the UK, Germany and Denmark confirm that system integration costs are only a fraction of the actual consumer price of electricity, ranging from € 0-4/MWh (consumer level), even under the most conservative assumptions. Integration costs at European level beyond penetration levels of about 25 % are not expected to increase steeply.

Their value depends on how the underlying system architecture changes over time as the amount of installed wind gradually increases, together with other generating technologies being removed or added to the system.

The main tool for providing a pan-European planning vision for grid infrastructure in line with the long-term EU policy targets should be the regularly updated ten year network development plan (TYNDP) drafted by the newly established body of European TSOs (ENTSO-E).

The TYNDP should reflect the Member States’ wind power generation forecasts, as provided in their National Renewable Energy Action Plans, realistically by providing sufficient corridors of adequate capacity.

Technologies such as underground HVDC should be used where it can accelerate the implementation. Accelerated development and standardization of transmission technology, more specifically multi-terminal HVDC VSC is necessary to avoid unnecessary delays. Neither the proper regulatory conditions, nor any attractive legal incentives for multinational transmission are in place.

Significant barriers to expansion of the network towards a truly pan-European grid exist, including public opposition to new power lines (causing very long lead times), high investment costs and financing needs and the absence of proper cost allocation and recovery methods for transmission lines serving more than just the national interest of a single country.

There is a wide range of short term actions that can optimize the use of the existing infrastructure and transmission corridors. These will help the European transmission system to take up the fast-growing wind power installed capacity, while maintaining high levels of system security. Dynamic line rating and rewiring with high-temperature conductors can significantly increase the available capacity of transmission corridors.

A range of power flow technologies (FACTS) and improved operational strategies are suitable immediate options to further optimize the utilization of the existing network. Some of these measures have already been adopted in the regions of Europe that have large amounts of wind power.

A transnational offshore grid should be constructed to improve the functioning of the Internal Electricity Market and to connect the expected increase in offshore wind energy capacity. Such an offshore grid would require investments in the order of €20 to €30 billion up to 2030.

Such an offshore grid should be built in stages, starting from TSOs’ existing plans and gradually moving to a meshed network. Demonstration projects connecting offshore wind farms to two or three countries should be built in the short term to test concepts and develop optimal technical and regulatory solutions.

The consequences for the onshore grid in terms of reinforcement in the coastal zones should be considered at an early stage. The creation of the necessary infrastructure for deploying offshore wind power should be coordinated at European level. The visions developed by EWEA – of 40 GW offshore wind energy capacity in 2020 and 150 GW by 2030 - and backed up by projects like OffshoreGrid should be taken forward and implemented by the European Commission and ENTSO-E. A suitable business model for investing in the onshore and offshore power grids and interconnectors should be rapidly introduced based on a regulated rate of return for investments.

With the very high shares of wind power and renewable generation expected in the future, the entire transmission and distribution system has to be designed and operated as an integrated unit, in order to optimally manage more distributed and flexible generation together with a more responsive demand side.

Innovative and effective measures need to be deployed such as ‘smart grids’, also termed ‘active networks’, ‘intelligent grids’ or ‘intelligent networks’, and assisted with adequate monitoring and control methods to manage high concentrations of variable generation, especially at distribution level. An important research task for the future is to investigate the use of controlled, dynamic loads to contribute to network services such as frequency response.

Proper regulatory frameworks need to be developed to provide attractive legal conditions and incentives to encourage cross-border transmission. This can be helped by building on the experience of "European Coordinators", which were appointed to facilitate the implementation of the most critical identified priority projects within the European TEN-E, particularly where the Coordinator has a clearly defined (and limited) objective. European energy regulators and ENTSO-E could implement regional committees to ensure regional/transnational infrastructure projects are swiftly completed.

Furthermore, the set-up of one central authorizing body within a Member State in charge of cross-border projects is worth exploring.

There is a great need for further short-term and longterm R&D in wind energy development at national and European level, in order to develop onshore and offshore technology even more, enable large scale renewable electricity to be integrated into Europe’s energy systems and maintain European companies’ strong global market position in wind energy technology. An appropriate framework for coordinating the identification of the research needs has been established by the EU’s Wind Energy Technology Platform (TPWind).

The research needs for the text ten years are presented in the European Wind Initiative, which has a budget of €6 billion, (the Wind Initiative is one of the European Industrial Initiatives which constitute part of the Strategic Energy Technology Plan). In the field of grid integration, TPWind has set up a dialogue with another Industrial Initiative: the Grid Initiative.

Research priorities for wind integration are:

* Solutions for grid connections between offshore wind farms and HVAC and HVDC grids, and the development of multi-terminal HV DC grids
* Wind plants that can provide system support, and novel control and operating modes such as virtual power plants
* Balancing power systems and market operation in view of design of future power systems with increased flexibility
* Transmission technologies, architecture and operational tools
* More active distribution networks and tools for distributed renewable management and demand-side response
* Tools for probabilistic planning and operation, including load and generation modelling, short-term forecasting of wind power and market tools for balancing and congestion management

## Electricity market design

Imperfect competition and market distortion are barriers to the integration of wind power in Europe. Examples of major imperfections are the threshold to market access for small and distributed wind power generators and the lack of information about spot market prices in neighboring markets during the allocation of cross-border capacity. In order for a power market to be truly competitive, sufficient transmission capacity is required between the market regions.

The European Commission together with relevant stakeholders (TSOs, regulators, power exchanges, producers, developers and traders) must enforce a comprehensive EU market integration strategy by implementing a target model and roadmap covering forward, day-ahead, intraday and balancing markets as well as capacity calculation and governance issues.

Regional Initiatives should converge into a single European market by 2015, as per the European Commission’s target. Furthermore, a single central auction office could be established in the EU.

Further market integration and the establishment of intra-day markets for balancing and cross border trade are highly important for integrating large amounts of offshore wind power.

A suitable legal and regulatory framework is required to enable efficient use of the interconnectors between participating countries. The adoption of the Third Liberalization Package in 2009 should accelerate the much needed reform of EU electricity markets and encourage the take-up of higher amounts of renewables, notably through the clear list of tasks it provides for TSOs and energy regulators. Network codes established in consultation with the market stakeholders should allow wind energy and other variable renewables to be integrated on a level playing field with other forms of generation.

Power systems with wind energy penetration levels of 10-12 % of gross electricity demand also need slower power plants (with start-up times above one hour) to participate in the intra-day rescheduling, as well as more flexible plants.

An international exchange of reserves in Europe would bring further advantages. The trade-off between saving money on flexible power plants and sharing of reserves across borders should be investigated with dedicated models.

The ongoing market integration across Europe - notably the establishment of regional markets - is an important building block for a future power system characterized by flexible and dynamic electricity markets, where market participants - including at the level of power demand - respond to price signals, fuel price risk and carbon price risk. Ongoing initiatives at regional level such as the Nordpool market, the Pentalateral Energy Forum, the Irish All-Island market and the Iberian MIBEL are all helping the integration of bigger amounts of variable renewables. The “North Seas Countries’ Offshore Grid Initiative” offers a way to create a North Sea market enabling the integration of large amounts of offshore wind power.

Redesigning the market in order to integrate maximum quantities of variable wind power would yield significant macro-economic benefits, through the reduction of the total operational cost of power generation. Intraday rescheduling of generators and application of intra-day wind power forecasting for low reserve requirements results in savings in the order of €250 million per year. The annual savings due to rescheduling power exchange for international trade would be in the order of €1-2 billion.

* Transparent and regularly updated information should be available to all market players in order to analyze the best market opportunities. It will not only ensure fairer market behavior, but also provide for the best possible imbalance management in a market-based and non-discriminatory way.
* Adequate mechanisms for market monitoring should be put in place. Consequently, the authorities must have full access to all relevant information so they can monitor market activities and implement any ex-post investigations and necessary measures to mitigate market power or prevent it potentially being abused.

## The merit order effect of large-scale wind integration

When there is a lot of wind power on the system, electricity wholesale market prices go down due to the so called merit order effect (MOE). Results from power market modeling show that with the expected wind power capacity reaching 265 GW in 2020, the MOE would amount to €11/MWh, reducing the average wholesale power price level from €85.8/MWh to €75/MWh. The total savings due to the MOE has been estimated at €41.7 billion/year in 2020. The merit order effect will be further influenced by fuel and carbon prices.

However, this figure assumes a fully functioning market. It also includes the long-term investments forecast and is therefore based on the long-term market equilibrium. Simulated generation volumes in 2020 require economic feasibility with regards to long run marginal costs. Wind capacity replaces the least cost efficient conventional capacities so that the system is in equilibrium. This shift in the technology mix is the main reason for the observed merit order effect.

In reality this might not always happen. Power market bids are based on short run marginal costs, plants that are not cost efficient might be needed in extreme situations, for example when there is a lot of wind power on the system. The short-term effects of wind power are mostly related to the variability of wind power.

The responding price volatility due to increased wind power stresses the cost efficiency of wind power generation. And in the real world, this would lead to a smaller merit order effect than analyzed in the future optimal market equilibrium.

Consequently, the results of the study have to be considered carefully, especially considering the assumed future capacity mix, which includes a lot of uncertainties. Moreover, results should not be directly compared to recent literature, which usually estimate the short term price effects of wind power. Here the market is not always in equilibrium and actual price differences and the merit order effect might therefore be very different.

Moreover, the study estimates the volume merit order effect referring to the total savings brought about due to wind power penetration during a particular year. Assuming that the entire power demand is purchased at the marginal cost of production, the overall volume of the MOE has been calculated at €41.7 billion/year in 2020. But this should not be seen as a purely socioeconomic benefit. A certain volume of this is redistributed from producer to consumer because decreased prices mean less income for power producers. Currently, only the long-term marginal generation which is replaced by wind has a real economic benefit, and this should be contrasted to the public support for extended wind power generation.

The sensitivity analysis resulted in an increase of the merit order effect by €1.9/MWh when fossil fuel prices (gas, coal and oil) are increased by 25 %. In the High fuel price case, wind power makes the power price drop from €87.7/MWh in the Reference scenario to €75/MWh in the Wind scenario. Comparing the resulting merit order effect in the High fuel case of €12.7/MWh to the Base case results of €10.8/MWh, the 25 % higher fuel price case gives a merit order effect that is 17.5 % higher.

The study showed that fuel prices have a major influence on power prices and marginal cost levels. The merit order effect has been mostly explained by the difference in the technology capacity and generation mix in the various scenarios, especially the differences in the development and utilization of coal and gas power technologies.

Investigating fuel price differences is therefore highly relevant. However, even stronger impacts on the merit order effect might be observed by changing the relative price differences of gas and coal price levels.

The study proved that carbon market assumptions and especially the resulting carbon price level will be a very important variable for the future power market and its price levels. Regarding the sensitivity of the assumed GHG emissions reduction target, the analysis illustrated higher equilibrium prices for the 30 % reduction case than for the 20 % reduction base case.

However, the results of the sensitivity analysis do very much depend on the assumptions for future abatement potential and costs in all EU ETS sectors, as well as in the industrial sectors.

## Roles and responsibilities

Wind power is capable of supplying a share of European electricity demand comparable to, or exceeding, the levels currently being met by conventional technologies such as fossil fuels, nuclear and large hydro power. Such penetration levels, however, would require cooperation among decision makers and stakeholders in the electricity sector in order to make the necessary changes to the European grid infrastructure, which was developed with traditional centralized power in mind. Stakeholders in this process should include:

* Wind energy sector: wind turbine and component manufacturers, project developers, wind farm operators, engineering and consulting companies, R&D institutes and national associations
* Power sector: transmission and distribution system operators and owners, power producers, energy suppliers, power engineering companies, R&D institutes, sector associations
* National and European energy regulation authorities
* Public authorities and bodies: energy agencies, ministries, national and regional authorities, European institutions, the Agency for the Cooperation of Energy Regulators (ACER) and the European Network of Transmission System Operators for Electricity (ENTSO-E)
* Users: industrial and private electricity consumers, energy service providers

# grid.jpgWind generation and wind plants: the essentials

## Wind generation and wind farms – the essentials

Although on a system-wide level wind power plants generate electricity just like any other plant, wind power has quite distinctive generation characteristics compared to conventional fuels. Firstly, there is the technical concept of the wind power plant. But perhaps more importantly, there is the variable nature of the wind resource driving the wind plant. Understanding these distinctive characteristics and their interaction with the other parts of the power system is the basis for integrating wind power into the grid.

## Wind power plants Wind power plant characteristics

In this section, the essential technical characteristics of wind power plants are described to facilitate understanding of their interaction with the electricity grid. This discussion is further divided into the wind turbine concept itself and the concepts used for wind power plants.

### Wind turbine electrical concepts

Grid connected wind turbines have gradually evolved over the last 30 years from simple constant speed turbines to fully variable speed systems that enable active output control. In much of the older generation technology, the wind turbine rotor speed is fixed by the frequency of the electricity grid, and the turbine operates below its peak efficiency in most of its operational wind speed range. This has proven to be a cost-effective and robust concept and it has been scaled up and optimized up to the 2 MW level.

The variable speed system uses power electronic converters that enable the grid frequency to be decoupled from real time rotational frequency as imposed by the instantaneous wind speed and the wind turbine control system. Variable speed operation enables performance optimization, reduces mechanical loading and at the same time delivers various options for active ‘power plant’ control. An essential feature of variable speed wind turbines is an active blade pitch control system, allowing full control of the aerodynamic power of the turbine (almost comparable to the fuel throttle of a combustion engine or gas turbine).

The decoupling of the electrical and rotor frequency absorbs wind speed fluctuations, allowing the rotor to act as a (accelerating and decelerating) flywheel, and thus smoothing out spikes in power, voltage and torque. It even enables the creation of synthetic inertia which is important in weak and poorly interconnected power systems with high levels of wind power.

Until the turn of the century, the constant speed concept dominated the market, and it still represents a significant percentage of the operating wind turbine population in pioneering countries such as Denmark, Spain and regions of Germany. However, newly installed wind turbines are mostly variable speed wind turbines.

Considering the wide range of technologies available, it is useful to categorize electrical wind turbine concepts by type of generator (including power electronics) and by method of power control into four types A, B, C and D.

The significant move towards the two last concepts (C + D represent almost 100 % of sales in 2010 so far) shows the efforts the industry has made to adapt the design to the requirements of improved grid compatibility with increasing wind power penetration. (The term ‘wind power penetration’ indicates the fraction of the gross (annual) electricity consumption that is covered by wind energy). Today’s share of the more flexible wind turbine types accounts for approximately 75 % of the total installed and operating wind turbine population worldwide. Because of historical factors (periods of strong market growth), as well as commercial (market position of manufacturers) and technical ones (grid codes) there can be large regional differences in the (cumulative) distribution of the wind turbine types in specific regions or countries. Especially in the first-mover countries (Germany, Denmark and Spain) there still is a significant amount of type A technology although this is rapidly changing, for example through repowering. For example, in Spain the distribution is: Type A - 18 %; Type B - 0 %; Type C - 77 %; Type D - 5 %.

### Wind power plant concepts and grid-friendly wind turbines

Wind turbines are usually placed in clusters (wind farms), with sizes ranging from a few MW up to several 100 MW. These clusters are connected to the grid as single generation units, therefore the term wind plants is the best suited. Whereas initially the emphasis on wind farm design was mainly on efficient and economic energy production that respected the rules of the grid operators, nowadays, with increasing wind power penetration, the demands of the grid operators have changed. In response to these demands, modern wind turbines and wind farms have developed the concept of the so-called wind energy power plant. The concept is essentially a wind farm with properties similar to a conventional power plant, with the exception that the fuel injection is variable. The operation of a wind energy power plant is designed in such a way that it can deliver a range of ancillary services to the power system.

Its control system is designed such that the power can be actively controlled, including ramping up and down similar to conventional generation plants. Wind power plants can and do positively contribute to system stability, fault recovery and voltage support in the system.

The properties described above greatly enhance the grid integration capability of wind power. In order to achieve high penetration levels, active control properties are essential to optimally share the power supply tasks together with other plants and to enhance network security. Section 2 explains how these wind power plant capabilities are reflected in network connection codes, and how specific wind power technologies are able to meet these requirements.

For essential power plant services, wind plants become comparable to conventional plants where the maximum possible values for both technologies are shown. Differences will remain due to the nature of variable generation dictated by meteorological input.

### Wind power performance indicators

An essential difference between wind plants and conventional power plants is that the output of wind plants very strongly depends on the characteristics (mainly the local wind climate) of the site where they are installed. The rated power, also known as the nameplate power, is the maximum power, which is reached only 1 % to 10 % of time. Most of the time wind turbines operate at partial load, depending on the wind speed. From the point of view of the power system, wind turbines can be regarded as production assets with an average power corresponding to 20 to 40 % of the rated power, with peaks that are three to five times higher.

Wind power performance indicators are related to the principal wind turbine specifications, that is rated power, and rotor diameter. The specific rated power is in the range of 300 – 500 W/m², where the area is the swept area of the rotor. Wind turbine electric power output is measured according to IEC 61400-12 [IEC 2005] and is represented in a power curve.

The power curve is used to estimate energy output at well defined site specific wind regimes (characterized by hub height wind speed and wind direction long-term frequency distribution). The energy output is standardized to long-term average annual energy output. The power curve is also used to derive the power output in short-term forecasting from 10-minute average wind speed values generated by forecast models. For power system studies, so-called regionally averaged power curves are used.

## Variability of wind power production

### Wind power: variable generation embedded in a variable electricity system

Wind power fluctuates over time, mainly under the influence of meteorological conditions. The variations occur on all time scales: seconds, minutes, hours, days, months, seasons, years. Understanding these variations and their predictability is of key importance to the integration and optimal utilization of the power system. Both demand and supply are inherently variable in electric power systems, and are designed to cope with this variability in an efficient way. Electrical demand is highly variable, dependent on a large number of factors, such as the weather (ambient temperature), daylight conditions, factory and TV schedules, and so on. The system operator needs to manage both predictable and unpredictable events in the grid, such as large conventional generators suddenly dropping off line and errors in demand forecast. Obviously wind energy’s share of production, which can be quite high, determines how much system operation will be affected by wind variability.

Variable versus intermittent generation Wind power is sometimes incorrectly considered to be an intermittent generator. This is misleading. At power system level, wind power does not start and stop at irregular intervals (which is the meaning of intermittent, and which is a characteristic of conventional generation). Even in extreme events such as storms it takes hours for most of the wind turbines in a system area to shut down.

For example in the storm of 8 January 2005, it took six hours for the aggregated wind power in Western Denmark to shut down from 90 % to 10 % production. Moreover, periods with zero wind power production are predictable and the transition to zero power is gradual over time. It is also worthwhile considering that the technical availability of wind turbines is very high (98 %) 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 the overall availability. Thus, the term intermittent is inappropriate for system wide wind power and the qualifier variable generation should be used.

### Short-term variability

For grid integration purposes, the short-term variability of wind power (from minutes to several hours) is the most important. It affects the scheduling of generation units, and balancing power and the determination of reserves needed. The short-term variability of wind power, as experienced in the power system, is determined by short-term wind variations (weather patterns), and the geographical spread of wind power plants.

The total variability experienced in the power system is determined by simultaneous variations in loads for all wind power plants and other generation units. The impact of the short-term variation of wind power on a power system depends on the amount of wind power capacity and on many factors specific to the power system in question (generation mix, degree of interconnection), as well as how effectively it is operated to handle the additional variability (use of forecasting, balancing strategy).

Analyzing the available power and wind measurements at typical wind plant locations allows the variations in net power output expected for a given time period, i.e. within a minute, within an hour or over several hours, to be quantified. The distinction between these specific time scales is made because this type of information corresponds to the various types of power plants for balancing. Experience and power system analyses show that the power system handles this short-term variability rather well.

### Variations within the minute: not a noticeable impact

The fast variations (seconds to one minute) of aggregated wind power output as a consequence of turbulence or transient events are quite small as can be seen in the operational data of wind farms. As a result they are hardly felt by the system.

### Variations within the hour are felt by the system at larger penetration levels

These variations (10-30 minutes) are not easy to predict, but they even out to a great extent with geographic dispersion of wind plants. Generally they remain within 10 % of installed wind power capacity for geographically distributed wind farms. The most significant variations in power output are related to wind speed variations in the range of 25 to 75 % of rated power, where the slope of the power curve is the steepest. The variations within an hour are significant for the power system and will influence balancing capacities when their magnitude becomes comparable to variations in demand; in general this will be from wind energy penetration levels of 5 to 10 % upwards.

### Variations in hourly timescale: predictable, but cause large amounts of uncertainty

Hourly, four-hourly and 12-hourly variations can mostly be predicted and so can be taken into account when scheduling power units to match the demand. In this time scale it is the uncertainty of the forecasts (predicted forecast error) that causes balancing needs, not the predicted variability itself. The system operator always considers the uncertainty of wind power predictions in relation to the errors in demand forecasts and other plant outages. It is useful to express these wind power variations as a percentage of installed wind power capacity.

When looking at wind power producing areas (instead of wind plants) it takes hours for most of the wind power capacity to go offline during a storm. Example: for the storm in Denmark on 8 January 2005, one of the biggest storms Denmark has seen in decades, it took six hours for the 2,400 MW of wind power in the West Denmark area (200 km²) to drop from 2,000 MW to 200 MW. The loss of power from a concentrated offshore wind farm area could happen within an hour. If most of the capacity comes from concentrated large offshore wind farms, a control method of recommended. The passage of a storm front can be predicted and appropriate control should be adopted to minimize the effects.

Extreme cases affecting system operation concern large active power output variations that have been wrongly predicted, e.g. a storm front prediction which contains uncertainty about how much wind power generation will be reduced as a result of it. Here, the accuracy of the prediction tools is of prime importance, as the next section will discuss. Moreover, technical possibilities for controlling the output of wind turbines to reduce a steep gradient in output power when a storm front is passing a wind farm exist, for example by using wind turbines provided with a storm control mode. However, ramp rates still can be quite significant when considering small areas.

For a larger geographical area, measures include the setting of a temporary cap on the output of all wind farms, the limitation of the maximum rate of change of wind farm output (ramp rate), for example by staggered starting or stopping, or by reducing positive ramp rates. Wind farms are highly controllable in this respect. Clearly, limiting the output of wind generation wastes free energy from a capital intensive power plant and should only be done when other means have been exhausted.

Of special interest for system operators is how wind variability affects the power flow in the transmission system. The TradeWind study investigated the effect of hourly wind power variations on the power flows in interconnectors. In addition to the observation that it is not easy to distinguish wind induced variations from other influences such as demand fluctuations, it appears that wind power forecast errors create significant uncertainty when predicting electricity flows in interconnectors.

### Long-term variability

The slower or long-term variations of wind power that affect how wind power is integrated into the power system include the seasonal variations and inter-annual variations caused by climatic effects. These are not very important for the daily operation and management of the grid, but do play a role in strategic power system planning.

Monthly and seasonal variations: These variations are important to electricity traders who have to deal with forward contracts where wind power volume has an influence on the price. They are equally important for planning the power system. It appears that both for electricity trading and for system planning purposes, the deviations, as for example derived from annual statistics of produced wind power, can be sufficiently hedged.

Inter-annual variations: These variations are relevant for long-term system planning, but not for daily power system operation. The annual variability of the mean wind speeds at sites across Europe tends to be similar and can reasonably be characterized by a normal distribution with a standard deviation of 6 %. The inter-annual variability of the wind resource is less than the variability of hydro inflow, for example. Finally, on a power system level the annual variations are influenced by the market growth of wind power and by the projected ratio of onshore to offshore wind power.

### Benefits of aggregation from geographically dispersed sites

With a wide regional distribution of wind turbines, there is a low correlation between short-term and local wind fluctuations and they largely balance each other out. This phenomenon has been studied extensively in many countries, and more recently in the European integration studies TradeWind, EWIS and OffshoreGrid. As a result the maximum wind power fluctuations experienced in the power system are reduced. One wind farm can show variations of over 20 % several hours per year, whereas the occurrence of variations of 15 % is practically zero for the total amount of Danish wind power.

The effect is even more pronounced when aggregating at European scale. Whereas offshore EU wind power still exhibits gradients of 8 % during a noticeable time, total EU wind power (onshore plus offshore) hardly shows hourly gradients in excess of 5 %. The smoothing effect on wind variability is clearly visible from Figure 6 where the variations of the wind power capacity factor (hourly values) over one month are shown for a small country (Belgium), a region of Europe (north-west) and for the whole of Europe.

A geographical spread of wind power plants across a power system is a highly effective way to deal with the issue of short term variability. Put another way, the more wind power plants in operation, the less impact from variability on system operation.

In addition to helping reduce fluctuations, the effect of geographically aggregating wind power plant output is an increased amount of firm wind power capacity in the system. In simple terms: the wind always blows somewhere. Furthermore, the wind never blows very hard everywhere at the same time. Wind power production peaks are reduced when looking at a larger area, which is important since absorbing power surges from wind plants is challenging for the system. The effect increases with the size of the area considered. Ideally, to maximize the smoothing effect, the wind speeds occurring in different parts of the system should be as uncorrelated as possible. Due to the typical size of weather patterns, the scale of aggregation needed to absorb a storm front is in the order of 1,500 km. By aggregating wind power Europe wide, the system can benefit from the balancing of high and low pressure areas over Europe. The economic case for smoothing wind power fluctuations through the use of transmission capacity is the subject of various European studies, both for onshore and offshore wind power.

A way of representing the beneficial effect of aggregation at power system scale is the load duration curve of wind power plants, which gives the frequency distribution of the partial load states of generated wind power. Aggregating wind power flattens the duration curve. A single offshore turbine in this example produces rated power for 1,500 hours and zero power during 1,000 hours. At the scale of a small country, total output is almost never zero and never higher than 90 % of installed capacity. For a large area like the EU, the maximum wind power produced at a given moment is 70 % of the total installed wind power capacity, whereas the minimum wind power production is never below 10 % of the installed wind capacity. This demonstrates how aggregation at European scale results in increasingly steady wind power output.

More detailed studies show that a more even distribution of wind plants over Europe would give an even smoother curve. Such studies develop guidelines for wind power plant planning and siting policies that support economic integration by minimizing the amount of additional balancing costs due to the wind variability.

A very important conclusion is that large-scale wind power cannot be aggregated to an optimal extent without a well interconnected grid. In this perspective, the grid plays a crucial role in aggregating the various wind power plant 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 exactly equivalent to the use of the grid to aggregate demand over interconnected areas.

## Variability and predictability of wind power production

### General

Accurate forecasts of the likely wind power output in the time intervals relevant to the scheduling of generation and transmission capacity allow system operators to manage the variability of wind power in the system. Prediction is key to managing wind power’s variability. The quality of wind power prediction has a beneficial effect on the amount of balancing reserves needed. Thus, forecasting wind power is important to its cost-effective integration in the power system.

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

Forecasting wind power production is different to forecasting other generation forms or forecasting the load. There is extensive experience with demand (load) forecasting, and consumption is more predictable than wind power. The quality of wind power forecasts is discussed below, and we explain how the accuracy of wind power prediction improves at shorter forecast horizons and when predicting for larger areas. In addition, ways for further reducing forecast error are highlighted.

### Forecasting tools

Short-term wind power prediction consists of many steps. For a forecasting horizon of more than six hours ahead, it starts with a Numerical Weather Prediction (NWP), which provides a wind prognosis, that is, the expected wind speed and direction in a future point in time. Subsequent steps involve applying the NWP model results to the wind power plant site, converting local wind speed to power, and applying the forecast to a whole region.

There are different approaches to forecasting wind power production. Typically, there are models that rely more on the physical description of a wind field and models that rely on statistical methods.

Both statistical and physical models can appear in an operational short-term forecasting model. The tools are also differentiated by different input data from the NWP model. Wind speed and direction at the wind power plant are used as a minimum. Some statistical and most physical models use additional parameters from the meteorological model, such as temperature gradients, wind speeds and directions at different heights above ground, and the pressure field.

All models scale down results from the NWP model’s coarse resolution, which in Europe for current models is between three and 15 km of horizontal resolution. In some areas with gentle terrain (Denmark, for example), this resolution is good enough for wind energy. In complex terrain (for example Spain), such resolution does not capture all the local effects around the wind power plant. If this is the case, additional meso-scale or micro-scale models can be employed, using the whole meteorological field of the NWP model in a radius of up to 400 km around the wind power plant. When using statistical models, the influence of orography on the accuracy of the outcome is less marked, and experience in Spain shows good results for complex terrains.

The science of short-term forecasting is developing very rapidly with remarkable results. In general, advanced statistical models tend to do well in most circumstances, but they require data accumulated over half a year before they perform very well. Physical tools, on the other hand, can create forecasts even before the wind power plant is erected. Later on, they can be improved using measured data. Some physical tools, however, require large computing facilities. In this case, they have to be run as a service by the forecaster, while computationally less demanding models can be installed by the client.

Recent practice is to use a combination of different input models and a combination of forecast tools to achieve a higher performance, as will be illustrated below.

### Accuracy of short-term wind power forecasting

Two major factors have a significant influence on the performance and accuracy of forecast tools, namely the size of the area considered and the prediction horizon:

* Regardless of the forecasting method used, the forecast error (RMSE) for a single wind power plant is between 10 % and 20 % of the installed wind power capacity for a forecast horizon of 36 hours, using current tools. After scaling up to aggregated wind power of a whole area the error drops below 10 % due to the smoothing effects. The larger the area, the better the overall prediction is.
* Forecast accuracy is reduced for longer prediction horizons. Thus, reducing the time needed between scheduling supply to the market and actual delivery (gate-closure time) would dramatically reduce unpredicted variability and, thereby, lead to a more efficient system operation without compromising system security.

The beneficial effect of using uncorrelated sites in forecasting is also seen by developers using a large geographically spread portfolio. It is not sufficient only to look at the average forecast error. While it is possible to have reasonable average prediction accuracy, due to the stochastic nature of wind, large forecast errors occur relatively frequently – as opposed to, for example, demand forecast errors.

In mathematical terms, the distribution of the error is not Gaussian. Large prediction errors occur relatively frequently. This is an important consideration for system reserve planning, as will be shown in Chapter 3. A way to cope with this is to use intra-day trading in combination with very short term forecasts (two to four hours) to reduce the forecast error.

There has been quite a dramatic improvement in the performance of forecasting tools since the beginning of the century. The joint effects of smoothing and improved forecasting tools are reflected in the learning curve, showing the development over time of the average error in Germany.

Improvements have been made by using ensemble predictions based on input from different weather models in one tool and combined prediction using a combination of different prediction tools. This results in a much more accurate prediction than using a single model.

For very short-term prediction – just two to four hours ahead, very accurate predictions are made but these need several kinds of data: a Numerical Weather Model, on-line wind power production data and real time wind measurements.

To summarize, different aspects have led to a significant improvement in short-term forecasting but, according to the experts, significant scope for further improvements remains.

When interpreting the predictability of wind power, it is not just wind forecasting accuracy that is relevant for balancing the system. It is the total sum of all demand and supply forecast errors that is relevant for system operation. At low penetration levels, the prediction error for wind has a small effect on the total system’s prediction error.

## Impacts of large-scale wind power integration on electricity systems

The impacts of wind power on the power system can be categorized into short-term and long-term effects. The short-term effects are created by balancing the system at the operational time scale (minutes to hours). The long-term effects are related to the contribution wind power can make to the adequacy of the system, that is its capability to meet peak load situations with high reliability.

### Impacts on the system are both local and system-wide

Locally, wind power plants, just like any other power station, interact with the grid voltage. Steady state voltage deviations, power quality and voltage control at or near wind power plant sites are all aspects to consider. Wind power can provide voltage control and active power control and wind power plants can reduce transmission and distribution losses when applied as distributed generation.

At system-wide scale there are other effects to consider.

Wind power plants affect the 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 centers and certainly at low penetration levels. On the other hand, large-scale wind power necessitates additional upgrades in transmission and distribution grid infrastructure, just as it is the case when any power plant is connected to a grid.

In order to connect remote good wind resource sites such as offshore wind plants to the load centers, new lines have to be constructed, just as it was necessary to build pipelines for oil and gas. Combining grid access with more general electricity trade, or locating large industrial consumers close to the wind plants could compensate for the lower utilization factor of the line due to the relatively low wind power capacity factor. In order to maximize the smoothing effects of geographically distributed wind, and to increase the level of firm power, cross border power flows reduce the challenges of managing a system with high levels of wind power. Wind power needs control regulation measures as does any other. Moreover, depending on the penetration level and local network characteristics, wind power impacts the efficiency of other generators in the system (and vice versa).

In the absence of a sufficiently intelligent and well-managed power exchange between regions or countries, a combination of (non-manageable) system demands and generation may result in situations where wind power has to be constrained. Finally wind power plays a role in maintaining the stability of the system and it contributes to security of supply as well as the robustness of the system.

### Wind power penetration determines its impact on the system

The impacts of the above described effects are very much dependent on the level of wind power penetration, the size of the grid, and the generation mix of electricity in the system. In 2010, the average energy penetration level of wind power in the EU is 5 %. EWEA’s target is to reach 14-17 % by 2020, 26-35 % by 2030 and 50 % by 2050.

Assessing how integration costs will increase beyond this ‘low to moderate’ level depends on the future evolution of the power system. Costs beyond penetration levels of about 25 % will depend on how underlying power system architecture changes over time as the amount of installed wind gradually increases, together with the decommissioning and construction of other generating technologies, to meet rapidly increasing demand for electricity and replacement of ageing capacity. The basic building blocks of the grid’s future architecture are: a flexible generation mix, interconnection between power systems to facilitate exchanges, a more responsive demand side, possibilities to interchange with other end-uses (heat, transport) and access to storage.

Up to a penetration level of 25 %, the integration costs have been analyzed in detail and are consistently shown to be a minor fraction of the wholesale value of wind power generation. Economic impacts and integration issues are very much dependent on the power system in question. The relevant characteristics are: the structure of the generation mix, its flexibility, the strength of the grid, the demand pattern, the power market mechanisms etc. as well as the structural and organizational aspects of the power system.

Technically, methods used by power engineers for decades can be applied to integrating wind power. But for integrating penetration levels typically higher than 25 %, new power system concepts may be necessary.

Such concepts should be considered from now on.

Looking at experience from existing large-scale integration in numerous regions of Europe, proves that this is not merely a theoretical discussion. The feasibility of large-scale penetration is proven already in areas where wind power already meets 20 %, 30 % or even 40 % of electricity consumption (Denmark, Ireland and regions of Germany and the Iberian Peninsula).

## Connecting wind power to the grid

In order for the network to operate safely and efficiently, all customers connected to a public electricity network, whether generators or consumers, must comply with agreed technical requirements. Electricity networks rely on generators to provide many of the control functions, and so the technical requirements for generators are necessarily 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. Furthermore, there may be technical requirements which are not referred to in the grid code, but apply to the project in the connection agreement, the power purchase agreement, special incentive schemes for ancillary services (for example in Germany and Spain) 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. The benefits are:

* Electricity system operators can be confident that their system will be secure no matter which generation projects and technologies are installed
* The amount of project-specific technical negotiation and design is minimized
* 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 equitably
* Different generator technologies are treated equally, as far as is possible

## Problems with grid code requirements for wind power

In the past, with vertically-integrated utilities, the same organization was responsible for the planning and operation of networks and giving access to generators, and therefore the technical requirements did not have to be particularly clearly defined or equitable.

Now, with legal and increased ownership separation due to new EU legislation, most prominently the third liberalization package between generators and network owners/operators, the technical requirements governing the relationship between generators and system operators must be more clearly defined The introduction of renewable generation has often complicated this process significantly, as these generators have characteristics which are different from the directly connected synchronous generators used in large conventional power plants. In some countries, this problem has introduced significant delays in the formation of grid code requirements for wind generation.

A specific problem today is the diversity of national codes and requirements. Another concern for the industry is the fact that requirements are not formulated precisely enough, leaving room for varying interpretations and lengthy discussions between concerned parties.

In some countries, a grid code has been produced specifically for wind power plants. In others, the aim has been to define the requirements as far as possible in a way which is independent of the generator technology. There are benefits in producing requirements which are as general as possible, and ones which treat all projects equally. However this can result in small projects facing the same requirements as the largest projects, which may not be technically justified or economically optimal. The European Wind Energy Association (EWEA) advocates a Europe-wide harmonization of requirements, with a code specifically formulated for wind power.

Some diversity may be justified because different systems may have different technical requirements due to differences in power mix, interconnection to neighboring countries and size. However, each country across the globe uses the same constant voltage and constant synchronous frequency system, it is only the physical parameters which are different. Grid code documents from the different EU countries are not at all homogeneous. Additionally, documents are often not available in English making them inaccessible.

These issues create unnecessary extra costs and require additional efforts from wind turbine designers, manufacturers, developers and operators. Requirements for the dimensioning, capabilities and behavior of wind power plants are often not clear, and are not always technically justified or economically sound from the point of view of the system and the consumer.

Historically, requirements have usually been written by the system operator at national level, while the energy regulatory body or government has an overview. However, in the interests of fairness and efficiency, the process for modifying requirements should be transparent, and should include consultations with generators, system users, equipment suppliers and other concerned parties. The process should also leave sufficient time for implementing modifications. The regulatory process initiated at European level to develop the first European network code on grid connection by ENTSO-E creates an opportunity for the wind power industry to get thoroughly involved.

The wind turbines that are currently available do not yet make full use of all possible control capabilities, for reasons of cost and also because grid codes do not yet take advantage of the full capabilities they could provide. As wind penetration increases, and as network operators gain experience with the new behavior of their systems, grid codes may become more demanding. However, new technical requirements should be based on an assessment of need, and on the best way to meet that need.

## An overview of the present grid code requirements for wind power

### Essential requirements

Technical grid code requirements and related documents vary from one electricity system to another. However, for simplicity, the typical requirements for generators can be grouped as follows:

* Tolerance - that is, the range of conditions on the electricity system for which wind power plants must continue to operate
* Control of reactive power: this often includes requirements to contribute to the control of voltage in the network
* Control of active power and frequency response
* Protective devices
* Power quality
* Visibility of the power plant in the network

It is important to note that these requirements are often specified at the Point of Connection (POC) of the wind power plant to the electricity network. In this case, the requirements are placed on the wind power plant. To achieve them the requirements for wind turbines may have to be different. Often wind turbine manufacturers will only specify the performance of their wind turbines, not the entire wind power plant. EWEA recommends that for transparency and inter-comparability, all grid codes should specify the requirements to apply at POC. It is also possible to meet some of the requirements by providing additional equipment separate from wind turbines. This is noted below where relevant.

### Tolerance

The wind power plant must continue to operate between minimum and maximum limits of voltage. Usually this is stated as steady-state quantities, though a wider range may apply for a limited duration.

The wind power plant must also continue to operate between minimum and maximum limits of frequency. Usually there is a range which is continuously applied, and several further more extreme short-term ranges. Early generation wind turbines (type A) are generally not capable of meeting wider operational frequency ranges as stipulated in several grid codes. However, the operation of a wind turbine in a wider frequency range is not really a complicated task as it mainly involves the thermal overloading of equipment, which has short thermal time-constants, in particular by using power electronic components. A possible solution for short-term overload capability consists of over sizing the converters, which in general can be done at reasonable cost. Increased operating temperature may also result in a reduced insulation lifetime. However, since operation at deviating frequency occurs rarely, the effect is negligible and can be reduced by limiting power output at the extremities of the frequency range. Therefore, in general, wind turbines can be made to operate in wider frequency ranges.

In systems with relatively high wind penetration, it is common that wind power plants are required to continue to operate during severe system disturbances, during which the voltage can drop to very low levels for very short periods. This is termed fault ride-through (FRT) or low voltage ride-through. A decade back, the TSOs required all wind turbines to disconnect during faults. Today they demand that wind turbines stay on the grid through these disturbances. Faults are inevitable on any electrical system and can be due to natural causes (e.g. lightning), equipment failure or third party damage. With relatively low transmission circuit impedances, such fault conditions can cause a large transient voltage depression across wide network areas.

Conventional large synchronous generators are expected to trip only if a permanent fault occurs in the circuit to which they are directly connected. Other generators that are connected to adjacent healthy circuits should remain connected and stable after the faulty circuits are disconnected, otherwise too much generation will be lost in addition to that disconnected by the original fault. Clearly, in this case the power system would be exposed to a loss of generation greater than the current maximum loss it is designed for, with the consequent danger of the system frequency dropping too rapidly and load shedding becoming necessary.

The requirements can be complex, and depend on the characteristics of the electricity system. Complying with the requirements may not be easy. It is feasible to use wind turbines which do not themselves comply with the FRT requirements, and meet the FRT requirements by installing additional equipment at the turbines or centrally within the wind power plant which can produce or consume reactive power.

### Reactive power and power factor 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 fixed power factor. The wind power plant is required to operate at a fixed power factor when generating, often this is 1.0. Often the required accuracy is not stated. The fixed value may be changed occasionally, for example during winter and summer.

Alternatively, the wind power plant can be asked 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 POC, but other locations may be specified. There may be requirements on the accuracy of control, and on the speed of response. Fast control may be difficult to achieve, depending on the capabilities of the wind power plant SCADA communications system.

Some wind turbine designs are able to provide these functions even when the wind turbine is not generating. This is potentially a very useful function for network operators, but it is not yet a common requirement. When considering FRT, it is also possible to meet these requirements with central reactive power compensation equipment.

### Active power control and frequency response

The system operator may add requirements to the code governing the extent to which the generator is capable of actively adjusting the output power. In addition he may require the generator to respond to grid frequency deviations.

For any generator, the ability to control frequency requires controlling a prime mover. Although the wind speed cannot be controlled, the power output of a wind turbine can be controlled by most modern turbines.

With pitch-regulated turbines, it is possible to reduce the output at any moment by pitching the blades. In principle, it is also possible to do this with stall-regulated turbines by shutting down individual turbines within a wind power plant, but this only provides relatively crude control.

The simplest, but most expensive, method is a cap. In this case the wind power plant (or a group of wind plants) is instructed to keep its output below a certain level. A more complex version of the cap is to require output to be kept to a fixed amount (delta) below the unconstrained output available from the wind.

In parallel with a cap, the wind power plant may also be instructed to control ramp rate, i.e. to limit the rate at which the output power can increase (due to increasing wind speed, or due to turbines returning to service after some outage). The ramp rate is defined over periods of, for example, one minute or 10 minutes.

This limits the demands the network operator has to make on other forms of generation to change their output rapidly.

Clearly it is not possible for the wind generation to control negative ramp rate at will, if the wind drops suddenly. However, with good wind forecasting tools, it is possible to predict a reduction in wind speed. Wind generation output can then be gradually reduced in advance of the wind speed reduction, thereby limiting the negative ramp rate to an acceptable level. The ability of generators to increase power output in order to support system frequency during an unexpected increase in demand escalation or after a loss of a network element is important for system operation.

Therefore, on systems with relatively high wind penetration, there is often a requirement for frequency response or frequency control. Pitch controlled wind turbines are capable of such system support only when they are set in advance at a level below the rated output and, of course, if wind is available. This allows them to provide primary and secondary frequency control.

This can take many forms, but the basic principle is that, when instructed, the wind power plant reduces its output power by a few percent, and then adjusts its output power in response to the system frequency. By increasing power when frequency is low or decreasing when frequency is high, the wind power plant provides a contribution to controlling the system frequency.

The problem associated with this type of network assistance from wind turbines is a reduced output and hence loss of income, which might not be offset by the primary control service. 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 consumption. For wind power this implies a loss of electricity produced at zero fuel costs, therefore it is not the cheapest option for the system, and should only be applied when other more cost effective options, such as fuel based technology curtailments, have been exhausted.

### Protective devices

Protective devices such as relays, fuses and circuit breakers are required in order to protect the wind power plant and the network from electrical faults. Careful co-ordination may be required, in order to ensure that all conceivable faults are dealt with safely and with the minimum disconnection of non-faulty equipment. Fault current is a related issue. In the event of an electrical fault in the network close to the wind power plant, some fault current will flow from the wind turbines into the fault. There may be requirements on the maximum or minimum permitted levels.

### Power quality

This term covers several separate issues [IEC, 2008] that determine the impact of wind turbines on the voltage quality of an electric power network. It applies in principle both to transmission and distribution networks, but is far more essential for the latter which are more susceptible to voltage fluctuations on the generation side.

The relevant parameters are active and reactive power, including maximum value, voltage fluctuations (flicker), number of switching operations (and resulting voltage variations), harmonic currents and related quantities.

The standard for characterizing the power quality of wind turbines and for the measurement of the related quantities is IEC 61400-21 [IEC, 2008]. The application of this standard enables a careful evaluation of the impact of wind power plants on the voltage quality in electrical networks. Instead of applying simplified rules which would be prohibitive for wind power, analysis of IEC 61400-21 methods is recommended (Tande in [Ackermann 2005] p.79) in order to carry out the following:

* Load flow analysis to assess whether slow voltage variations remain within acceptable limits
* Measurements and comparison with applicable limits of maximum flicker emission which can be caused by wind turbines starting or stopping, or in continuous operation
* Assessment of possible voltage dips due to wind turbine start-up, stops or by energisation of transformers
* Estimation of maximum harmonic current and comparison with applicable limits

### Visibility

In a power system with large contributions from decentralized plants, it is essential for the system operator to obtain on-line information about the actual operational conditions at the decentralized plants. Access to such information can, for example, be critical during network faults when fast decisions have to be made to reschedule generators and switch network elements. For this purpose, agreements are made between the system operator and the wind plant operators on communicating signals such as active and reactive power, technical availability and other relevant status signals. On-line information about wind plants can also be necessary for system operation for the purpose of short-term forecasting of the output of wind plants in a region.

### Future developments

As noted above, technical requirements may well become more onerous for wind generation as wind power penetration levels increase in the future.

One possible new requirement is for an inertia function. The spinning inertias in conventional power plants provide considerable benefits to the power system by acting as a flywheel, and thereby reducing the short term effects of imbalances of supply and demand. Variable speed wind turbines have no such equivalent effect, but in principle their control systems could provide a function which mimics the effect of inertia. There may also be a move towards markets for services, rather than mandatory requirements. This would be economically more efficient, as the generator best able to provide the service will be contracted to provide it. For example, if a wind power plant provides a useful service to the network operator in controlling voltages, i.e. it does more than just correct its own negative effects, then the wind power plant should be paid for this service. Whether this is cheaper than other options available to the network operator should be determined by the market. Moreover, due to the power electronics in electrical conversion systems, wind power plants can provide some network services, especially voltage control, more rapidly than conventional thermal plants.

## Two-step process for grid code harmonization in Europe

There is considerable potential for improving the process of wind power integration by harmonizing grid codes requirements for wind power. Such a process will benefit all the stakeholders involved in the integration of wind power. A systematic approach to setting a European grid code harmonization process in motion was proposed by EWEA in 2008. Harmonization does not automatically mean that the maximum and most stringent requirements should apply everywhere, rather it is a process of cleaning out technically unjustified requirements and creating a transparent, understandable, comprehensive and well-defined set of requirements according to common definitions and specifications and optimized to the power systems where they apply.

A two-step harmonization strategy introduced by EWEA consists firstly of a structural harmonization, and secondly a technical harmonization. Together, the two forms of harmonization should particularly benefit those system operators that have not yet developed their own customized grid code requirements for wind powered plants.

Structural harmonization consists of establishing a grid code template with a fixed and common structure (sequence and chapters), designations, definitions, parameters and units. The key aim of the structural harmonization process is to establish an accepted framework for an efficient grid code layout. Such a template was launched16 by EWEA in 2009.

Technical harmonization can be seen as a more long term process which works by adapting existing grid code parameters following the template of the aforementioned new grid code. The process is to be implemented through co-operation between TSOs (ENTSOE), the wind power industry and regulatory bodies (ACER). The implementation of the Third Liberalization package as described below provides the proper enabling legal and institutional framework at EU level.

In the developing European internal electricity market, national networks have to be interlinked in a more efficient way. They must be operated as part of an integrated European grid to enable the necessary cross border exchanges. This requires harmonized codes and technical standards, including grid connection requirements. However, the national power systems in Europe today are so different that a full harmonization cannot and should not be carried out straight away.

The implementation of further liberalization measures in the energy sector in Europe, as imposed by the so called Third Liberalization Package, involves the creation of a European network code for connection. This process involves several steps in which European TSOs and European regulators play a crucial role. Basically, the regulators (ACER) set out the framework for the code in a so called framework guideline. Consequently, the TSOs draft the European code according to the terms set out in the framework guideline. Once established, the code will be imposed throughout European and national legislation (comitology). The process asks for an open consultation with the relevant industry associations when drafting the codes. With this, the legal framework has been set for further developing harmonized grid code requirements through co-operation between TSOs and the wind energy sector.

At the same time, this creates the opportunity to strike a proper balance between requirements at wind plant and at network level, in order to ensure the most efficient and economically sound connection solutions.

EWEA recommends that in this future European code for network connection, there is a clear grouping of wind power related grid code requirements in a separate chapter to ensure the maximum level of clarity and an adequate valuation of the specific power plant capabilities of wind power.

# Power system operations with large amounts of wind power

## Introduction

While today’s power systems are able to integrate ever growing amounts of wind energy, an innovative approach to expanding and running the systems is necessary, especially at higher penetration levels. Many of the studies mentioned in this chapter have concluded that it is possible to efficiently integrate large amounts of wind power (20 % and up) when the power system is being developed in an evolutionary way. Many factors can help with this, and this chapter of the report attempts to address the major ones. It shows which changes are necessary to the way various parts of the power system (generation, network and demand side) are operated. As a major principle, in order to efficiently integrate a large amount of variable renewable generation like wind power, the system should be designed with a higher degree of flexibility through a combination of flexible generating units, flexibility on the demand side, availability of interconnection capacity and a set of power market rules that enable a cost-effective use of the flexibility resources.

## Balancing demand, conventional generation and wind power

Just like with any other major power source, when significant amounts of new wind generation are integrated in an economic and orderly way into the power supply, (relative) extra reserve power is required, the power cost changes, technical measures must be taken and the power market redesigned. It is important to note that system balancing requirements are not assigned to back up a particular plant type (e.g. wind), but to deal with the overall uncertainty in the balance between demand and generation. Moreover, the uncertainty to be managed in system operation is driven by the combined effect of the fluctuations both in demand, and in generation from conventional and renewable generation. These individual fluctuations are generally not correlated, which has an overall smoothing effect and consequently, a beneficial impact on system integration cost.

System operators’ operational routines vary according to the synchronous systems and the countries they are in. The terminology of the reserves used also varies. In this document, we put the reserves into two groups according to the time scale they work in: primary reserve for all reserves operating in the second/minute time scale and secondary/tertiary reserve for all reserves operating in the 10 minute/hour time scale. Primary reserve is also called instantaneous, frequency response, or automatic reserve or regulation. Secondary reserve is also called fast reserve and tertiary reserve is also called long-term reserve (the term ‘load following reserve’ is also used for the latter two).

Wind power’s impacts on power system balancing can be seen over several time scales, from minutes to hours, up to the day-ahead time scale. It can be seen both from experience and from tests carried out that the variability of wind power from one to six hours poses the most significant requirements to system balancing, because of the magnitude of the variability and limitations in forecast systems. At present, frequency control (time scale of seconds) and inertial response are not crucial problems when integrating wind power into large interconnected power systems. They can however be a challenge for small systems and will become more of a challenge for systems with high penetration in the future.

## Effect of wind power on scheduling of reserves

The amount of additional reserve capacity and the corresponding costs when increasing the penetration of wind power are being explored by power engineers in many countries. The investigations simulate system operation and analyze the effect of an increasing amount of wind power for different types of generation mix. The increase in short term reserve requirement is mostly estimated by statistical methods that combine the variability or forecast errors of wind power to that of load and investigates the increase in the largest variations seen by the system. General conclusions on increasing the balancing requirement will depend on factors such as the region size, initial load variations and how concentrated/distributed wind power is sited.

In 2006 an agreement on international cooperation was set up under the IEA Task 251 to compare and analyze the outcome of different national power system studies. The 2009 report of this Task 25 [Holttinen, 2009] gives generalized conclusions based on studies from Denmark, Finland, Norway, Sweden, Germany, Ireland, Spain, Netherlands, Portugal, the UK and the USA. This experience is used in this report to illustrate the issues and solutions surrounding the reserves question. The value of the combined assessment in the IEA Task 25 is that it allows the systematic relationship of the increased demand of system reserves to be shown as a function of wind energy penetration.

When considering the impacts of wind power on the different types of reserve requirements, it is of central importance to make a clear distinction between the need for flexibility in longer time scales of several hours to a day (power plants that can follow net load variation) and the need for reserves that can be activated in seconds or minutes (power plants that can follow unpredicted net load variations – demand minus wind).

### Primary reserves

Wind power development will have only a small influence on the amount of primary reserves needed. On time scales of seconds/minutes, rapid variations in total wind power capacity output occur randomly, like the load variations that already exist. When aggregated with load and generation variations, the increase in variability due to wind is very small. Furthermore, the amount of primary reserve allocated to the power systems is dominated by the potential outages of large thermal generation plants, so it is more than large enough to cope with the very rapid variations in wind. In practice, power plant generation is scheduled to match the anticipated trends in demand so it can be balanced with the supply. For any deviations from the anticipated trends, primary and secondary reserves are operated continuously to keep system frequency close to its nominal value. In addition, wind power can provide its own primary reserve.

### Secondary and tertiary reserves

On the time scale of 10-30 minutes the impact of wind power on the need for secondary reserves will only be significant and increase due to wind energy penetration levels of more than 10 %.

Wind power has a much more significant impact on the way conventional units are scheduled to follow the load (hour to day time-scales). In the absence of a perfect forecast, the unit-commitment decision will be surrounded by uncertainty additional to the normal uncertainty associated with load and conventional generation outage forecasting. The result is that sometimes a unit might be committed when it is not needed, and sometimes a unit might not be committed when it is needed. Here, the generation mix of the power system determines how the scheduling will change according to the expected wind power production, the more flexible power units there are, the later the unit commitment decisions need to be made.

Estimates for the increase in short-term reserve balancing capacities [Holttinen, 2009] show a wide range: 1-15 % of installed wind power capacity at 10 % penetration (of gross demand) and 4-18 % of installed wind power capacity at 20 % penetration.

### Discussion of additional reserve requirements

Differences in the power system’s operational routines explain a lot of the differences, notably how often the forecasts of load and wind are updated. If a re-dispatch based on a forecast update is done in four to six hours, this would lower the reserve requirements and costs of integrating wind compared with scheduling based on only day-ahead forecasts.

Emerging intra-day markets take this particularity into account by giving the opportunity for hourly updates. The way the power system is operated regarding the time lapse between forecast schedules and delivery has a decisive impact on the degree of uncertainty wind power will bring and so will indirectly determine the amount of additional reserves required.

It is important to note that an increase in reserve requirements does not necessarily mean new investments will have to be made, for example the construction of new thermal power plants. From analysis of the system and from experience it follows that the forecast uncertainty of incidental combinations of wind power generation and demand is critical for assessing the need for additional reserves, especially the “low demand high wind” combination. Additional flexibility from conventional units is especially critical in situations of low load and high wind [Ummels, 2008] because in such situations the thermal plant may have to be ramped up fast because of sudden drops in wind power generation. More generally, increased wind power will mean conventional thermal units will have to be operated in a more flexible manner than if there were no wind energy.

## Short term forecasting to support system balancing

Wind power forecasting has become essential for operating systems with a significant share of wind power. Forecast systems are used by various parties, including network operators, energy traders and wind plant operators. The main benefits are reduced costs and improved system security. Forecasting enables wind power to be traded and integrated in the scheduling system, which eventually ensures that demand and power supply are balanced and makes use of the most cost-effective generation sources.

In regions with a high level of penetration, which include regions in 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 operations of other plants, and for trading purposes. Areas of power system operation where system operators specifically benefit from wind power forecasts include:

* Routine forecasts: increasing the confidence levels
* Forecasting in critical periods, e.g. times of maximum load (including ramps)
* Forecasting of significant aggregated wind power fluctuations (ramps)
* Severe weather forecasts

Forecasting has a potentially high economic value to the system, especially with large amounts of wind power. A study from the US (California) [GE/AWST 2007] has quantified the cost-benefit ratio to be 1:100. Large additional investments are required to effectively implement centralized forecast systems, especially investments in observation networks in order to provide the necessary meteorological and operational data. Such investments are justified by the significant reductions they entail to the operational costs of power generation.

The nature of the wind power forecast error statistics leads to the following important observation: the total amount of balancing energy stems from the average forecast error; however, the need for reserve power is dependent mainly on the extreme forecast error. Therefore, apart from using the best available forecasts, the method recommended for reducing the required balancing power (and thus reserve plant capacity) is to keep the forecast error as low as possible by intra-day trading in combination with very short-term forecasting (2-4 hours ahead).

## Additional balancing costs

The overview of studies investigating wind penetrations of up to 20 % of gross demand (energy) in national or regional power systems [Holttinen, 2009], concludes that increases in system operating costs arising from wind variability and uncertainty amount to about €1-4/MWh wind energy produced. This cost is normalized per MWh of wind energy produced and refers to the wholesale price of electricity in most markets.

The studies calculate the additional costs of adding different amounts of wind power as compared to a situation without any. The costs of variability are also addressed by comparing simulations assuming constant (flat) wind energy to simulations with varying wind energy.

Both the allocation and the use of reserves create additional costs. The consensus from most studies made so far is that for wind energy penetration levels up to 20 %, the extra reserve requirements needed for larger amounts of wind power is already available from conventional power plants in the system. That is, no new reserves would be required, and thus additional investments in new plants wouldn’t be necessary. Only the increased use of dedicated reserves, or increased part-load plant requirement, will cause extra costs (energy part) – and there is also an additional investment cost related to the additional flexibility required from conventional plants. The costs themselves depend on the marginal costs for providing regulation or mitigation methods used in the power system as well as on the power market rules.

The main contributing factors to lower balancing costs are:

* Larger areas: Large balancing areas offer the benefits of lower variability. They also help decrease the amount of forecast errors in wind power forecasts, and thus reduce the amount of unforeseen imbalance. Large areas favor 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.
* Reducing gate-closure times: This means operating the power system close to the delivery hour. For example, a re-dispatch, based on a 4–6 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 intra-day markets will facilitate larger amounts of wind energy in the system.
* Improving the efficiency of the forecast systems: Balancing costs would be decreased if wind power forecast accuracy was improved, leaving only small deviations in the rest of the power system. Experience from different countries (Germany, Spain and Ireland), shows that the accuracy of the forecast has been improved in several ways, ranging from improvements in meteorological data supply to the use of ensemble predictions and combined forecasting.

In the latter two, the quality of the forecast is improved by making a balanced combination of different data sources and methods in the prediction process.

## Improved wind power management

To enable a power system to integrate large amounts of wind power, optimized wind power operation, management and control are necessary. The pooling of several wind farms into clusters in the GW range will make new options feasible for an optimized integration of variable generation into electricity supply systems. New concepts for cluster management will include the aggregation of geographically dispersed wind farms according to various criteria, for the purpose of an optimized network management and optimized (conventional) generation scheduling. The clusters will be operated and controlled like large conventional power plants.

In view of the probable wind power forecast errors, the difference between forecast and actual supply must be minimized by means of control strategies of wind farm clusters to ensure the generation schedule is maintained. Power output will in this case be controlled in accordance with the schedule determined by the short-term forecasts. This strategy has a large impact on the operation of the wind farms and requires announced and actual generation to be matched on a minute-to-minute basis. The schedule should be carried out within a certain tolerance band (which should itself be determined by forecast error). Time-variable set points should be constantly generated and refreshed for optimum interaction between wind farms and wind farm cluster management. It is assumed that short-term forecasting for wind farms and cluster regions is used and continually updated for this kind of operation management. Wind farm control strategies include:

* Limitation of power output
* Energy control
* Capacity control
* Minimization of ramp rates

Non-controllable wind farms can be supported by controllable ones in a particular cluster. This strategy will allow hybrid clusters to fulfill their requirements.

### Contribution of wind power in congestion management

From time to time wind power generation achieves, and can exceed, the maximum temperature allowed of grid components. The situations can be foreseen and avoided by network simulations based on wind generation forecasting and the limitation of wind power output to a pre-calculated threshold. Different wind farms in a cluster can be curtailed differently, thus giving an opportunity for an economical optimization of the process.

### Losses reduction, optimization of active and reactive power flows

Wind power generation is variable not only over time, but also geographically, and geographical variations can lead to power flows over large distances and associated power losses. Such situations can be identified beforehand and reduced or even completely prevented by the interaction of wind clusters with conventional power plants. The transmission of reactive power can be managed in a similar way.

Implementation of these operating methods will significantly increase wind energy’s economic value to the system by keeping the additional balancing costs to a minimum. Based on innovative wind farm operational control, a control unit between system operators and wind farm clusters, wind farm cluster management will enable profile based generation (i.e. the output of a generation cluster following a certain time schedule facilitating system operation) and management of the following tasks:

* taking account of data from online acquisition and prediction
* aggregation and distribution of predicted power generation to different clusters
* consideration of network restrictions arising from network topology
* consideration of restrictions arising from power plant scheduling and electricity trading
* scaling of threshold values
* allocation of target values to different clusters and generation plants

The combination and adjustment of advanced wind farm control systems for cluster management will be achieved by the wind farms cluster management.

Furthermore, the cluster management prepares and administrates profiles for the plant control systems based on forecasts, operating data, online-acquired power output and defaults from the system operators.

# Upgrading electricity networks: challenges and solutions

## Drivers and barriers for network upgrades

Upgrading the European electric power network infrastructure at transmission and distribution level is perhaps the most fundamental step on the way to reaching the EU’s mandatory target to meet 20 % of our energy from renewable energy sources, including increasing the share of renewable electricity from 15 % to 34 % by 2020. Equally, renewable energy – together with security of supply, energy independence and developing the internal market - has become a significant driver for expanding, modernizing and interconnecting the European electricity networks. Better interconnected networks bring significant benefits for dispersed renewable power by aggregating (bringing together) dispersed (uncorrelated) generation leading to continental smoothing, improved predictability and a higher contribution from wind power capacity to peak demand.

The transmission systems in Europe were designed and built for a very different power mix to the one we have today and will have tomorrow. In fact, in its early days 100 years ago, electricity was supplied from distributed generation and it is only for the last 50 years or less that transmission systems have been planned for a supply concept based on ever larger central units. Historically, there was little European cross-border transmission capacity between UCTE countries or between the UCTE and other synchronous zones (Nordel, UK, Ireland).

At that stage, using substantial amounts of renewable energy, with the exception of large hydro, was not considered; neither were the concepts of virtual power plants or of trading electricity on a spot market. The changing flows in the system demonstrate the need to expand and reinforce the grids to optimize the transportation of power from generators to consumers.

More flexibility, new technology and grid management concepts also need to be introduced to prepare the power systems for future distributed and variable generation. In the debate about future networks, two concepts are omnipresent: the Supergrid and Smart Grids. Although these terms do not have a fixed definition, their widespread use testifies to a consensus that network upgrades are generally expected to be take the form of a highway-type interconnection (Supergrid) with more communication and intelligence (Smart grids), properties that are certainly advantageous to large-scale integration of wind power. Another major driver for grid upgrades is the emerging internal electricity market (IEM) in Europe, requiring sufficient transport capacities between regions and nations to enable effective competition in the power market to the benefit of European consumers.

In its first edition of the Ten Year Network Development Plan [ENTSO-E, 2010], the transmission system operators, ENTSO-E, estimated the required expansion of the network – focusing on lines of European interest – for the years up to 2020, quantifying the drivers in terms of system security (SoS), renewables (RES) and electricity markets (IEM).

In addition to the upgraded and new network infrastructure, a proper legal framework is needed, so the capacity can be fully exploited. At European level, two major initiatives contain basic elements of such a framework:

* The European Renewable Energy Directive (2009) stipulates that national governments and TSOs should guarantee renewables sufficient transmission capacity and fair access to the transmission network.
* The mandatory ownership unbundling of generation and transmission as required by the proposed third Liberalization Package (2008) should provide the legal basis to guarantee a level playing field with other generators.

In practice, carrying out the required network upgrades, especially building new lines, is a very lengthy process. Therefore, and because of the difference in speed between wind power development and transmission development, fair access rules are needed for the majority of instances where power lines are shared between wind energy and other power generators. Uniform rules do not yet exist at European level, and grid access for wind energy is currently conducted in a rather ad-hoc way. Some countries such as Germany and Spain take the recommendation from the 2009 RES Directive into account, and grant priority access to wind power to a certain extent. In practice, in cases where available grid capacity is limited, the principle of ‘connect and manage’ is often followed. At distribution level it is often ‘fit and forget’. The wide range of different times taken to obtain a grid connection permit for a wind farm in the different EU countries (as identified in the 2010 WindBarriers project) reflects the lack of consistency between national policies in Europe in dealing with the issue of joint planning for new (renewable) generation and for network expansion.

Adapting the transmission infrastructure to uncertain future needs is a complex process that is subject to strategic planning, and includes the following steps:

* Short term: optimization of the utilization of the transmission network
* Mid- and long term: creation of Europe-wide onshore and offshore grids

There are some barriers related to network upgrades and extensions, specifically the construction of new lines:

* Long lead times in view of the planning procedures. Nowadays in many regions in Europe it can take seven or more years to get from the initial idea for a new overhead line to its actual implementation, mainly because of lengthy planning and permitting procedures influenced by social acceptance problems
* Need for substantial amounts of capital for network upgrades
* Absence of proper cost allocation mechanisms for multi-country and multi-user transmission lines
* Planning of grid investments and planning of wind farms are largely independent processes

Transmission planning in Europe is at a critical stage.

Crucial political decisions have been taken at European level in the past five years, including the RES Directive (2009/28) and the next big step in energy liberalization, the Third Package. The most relevant development in terms of network infrastructure is the creation of a pan-European association for network operators, ENTSO-E, as well as the revision of Directives spelling out the role of network operators and regulators in a more liberalized market. In this respect, the TYNDP of the ENTSO-E should be the main tool for providing a pan-European planning vision for grid infrastructure in line with long-term EU policy targets for renewables, including the National Renewable Energy Action Plans (NREAPs).

## Immediate opportunities for upgrade: optimal use of the network

In the short term, and at relatively low levels of wind power penetration, transmission upgrades often coincide with methods of congestion management and optimization in the transmission system. Moreover, there exist technical measures which do not involve excessive expenditure, but instead avoid or postpone network investments. A number of attractive technologies exist that have significant potentials for accelerating grid capacity and easing wind energy integration are discussed here.

### Dynamic line rating with temperature monitoring

Dynamic line rating allows existing power lines to be used in a more optimal way by operating them at higher capacities by monitoring the temperature. Transmission capacity increases with the cooling effect of certain weather conditions, such as the wind blowing.

The amount of power produced by wind power plants is obviously higher when it is windy. Hence, the use of dynamic line rating with temperature monitoring would ease the transmission constraints associated with a large wind power output. The amount of wind power produced also tends to be higher at night and during cooler periods of the year, so again dynamic line rating would allow more transmission capacity to be used. This approach is already in use in a few places, and industrial solutions are available1. The standardization of this method is ongoing. A study for Germany has quantified the possibilities for dynamic line rating, and found significant opportunities depending on the regional climate and wind conditions.

### Rewiring with high temperature conductors

Rewiring existing lines with low sag, high-temperature wires offers the possibility to increase the overhead line capacity by up to 50 %, as electrical current carrying capacity directly depends on the power line sag and the line temperature. Depending on the specific situation, rewiring may be possible without having to obtain a permit, thus offering a fast way to significant transmission capacity enhancement.

### Power flow control devices

The installation of power flow control devices in selected places in the network can help to optimize the utilization of the existing grid. Flexible AC Transmission Systems (FACTS2) are widely used to enhance stability in power systems, but some FACTS solutions also support power flow control. Physically, in large radial European transmission networks, there is a lack of power flow controllability, because there is only one way for the power to flow. The lack of controllability can sometimes lead to congestion on a specific transmission line while there is still capacity on alternative lines. Since large-scale wind power changes the pattern of generation in the grid, the growth of wind power can increase the economic feasibility of AC power flow control. An example of this was shown in TradeWind simulations, where increased wind power generation in central Norway would cause the corridor to Sweden to overload while there was still free capacity on the corridor to south Norway. One option in this case would be to reduce the hydro generation in central Norway when the wind speeds are high, but according to research, this would not be the preferred market solution if there were a possibility to control the AC flow. Consequently, it may be economically attractive to control the flow in certain AC lines, even if it would cost in terms of investment in auxiliary equipment. Thus, power flow control can ensure that existing transmission lines are utilized to the maximum, which is important given the public’s reluctance to accept additional power lines, and the long-term project implementation which is normally associated with reinforcement of transmission systems.

### Technologies that can help implement new network operation strategies

An assessment of the online dynamic network security by Wide Area Monitoring (WAMS) may substantially reduce traditional conservative assumptions about operational conditions, and thus increase the actual transfer capability of a power system. WAMS uses advanced GPS based surveillance tools to enable network operators to react in close-to-real-time for trading, fault prevention and asset management, and thus maintain the required reliability and system performance with increasing renewable generation. There are some organizational and regulatory challenges for the wide-spread introduction of WAMS, notable the need for standardized monitoring technologies, synchronized data acquisition and online data exchange.

### Using distributed wind plants to improve transmission operation

Investments in the grid also can be reduced by the technical capabilities of the wind farms themselves, in particular when combined with technologies that improve the control of reactive power. This could for example be achieved by installing wind power plants at selected sites along the transmission grid especially for the purpose of grid support, which has a similar effect to installing FACTS. The advantage of wind plants over FACTS is that they produce energy in addition to grid support.

## Longer term improvements to European transmission planning

Transmission planning is based on a careful assessment of the expected development of generation – including wind power – and demand, as well as an analysis of the current network infrastructure (congestions/ replacement needs) to maintain security of supply. Input for these analyses is delivered by a range of studies as explained in the next section.

The development of offshore grids is of course part of this process. However because of the specific issues involved, offshore grids are dealt with in a separate section.

## Recommendations from European studies

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 wind power integration. The most important recent international studies are TradeWind (www. trade-wind.eu) and EWIS (www.wind-integration.eu). Studies like these, which analyse the grid extensively – including both steady-state load flow and dynamic system stability analysis – are essential for quantifying the reinforcement needed to maintain adequate transmission with increasing wind power penetration.

### TradeWind findings on grid upgrades

The TradeWind study (2006-2009) was undertaken by a wind energy sector consortium coordinated by EWEA. The project investigated grid upgrade scenarios at European level that would be needed to enable wind energy penetration of up to 25 %, using wind power capacity scenarios up to 2030.

TradeWind used a network model to look at how congestion develops in the interconnectors as more wind is connected to the system. The model applied reinforcements to the transmission lines that showed the largest congestions, in three different stages, and calculated how far these reinforcements could reduce the operational cost of power generation.

The TradeWind simulations show that increasing wind power capacity in Europe leads to increased cross border energy exchange and more severe cross-border transmission bottlenecks in the future. With the amounts of wind power capacity expected in 2020 and 2030, congestion on several national borders (France, the UK, Ireland, Sweden, Germany, Greece) will be severe, if left unsolved. The major transmission bottlenecks were identified, with special attention paid to the interconnectors of ‘European interest’ according to the Trans-European Networks program of the European Commission. The effect of stormy weather conditions on cross-border flow was also investigated.

Wind power forecast errors result in deviations between the actual and expected cross-border power flows on most interconnectors over a substantial part of the time and will further exacerbate any congestion.

Based on the costs of these congestions, network upgrades that would relieve existing and future structural congestion in the interconnections were shown to have significant economic benefits.

More specifically, TradeWind identified 42 interconnectors and a corresponding time schedule for upgrading that would benefit the European power system and its ability to integrate wind power. In a perfect market, the upgrades would bring savings in operational costs of power generation of €1,500 million/year, justifying network investments in the order of €22 billion for wind power scenarios up to 2030.

An important finding of TradeWind was that the grid reinforcements would bring substantial economic benefits to the end consumer, no matter how much wind power was included. A preliminary economic analysis of a meshed offshore grid linking 120 GW offshore wind farms in the North Sea and the Baltic Sea and the onshore transmission grid showed that it compares favorably to a radial connection for individual wind farms, mainly due to the greater flexibility that it offers, as well as the benefits for international trading of electricity.

TradeWind was the first scientific project to study the Europe-wide impact of high amounts of wind power on the transmission grids. Parts of the methodology and the models have been taken up in further projects such as RealiseGrid, OffshoreGrid, RE-Shaping.

### EWIS findings on necessary grid upgrades

EWIS (European Wind Integration Study) (2007-2010) was carried out by 15 European TSOs. The project investigated the changes to the grid that would be needed to enable the wind power capacity foreseen for 2015, using the same assumptions as TradeWind on installed wind power capacities for 2015. The EWIS “Best-Estimate” scenario corresponds to the TradeWind “2015 Medium” scenario, and the EWIS “Optimistic” scenario corresponds to the TradeWind “2015 High” scenario. EWIS also created an “Enhanced Network” scenario, which was business as usual plus some reinforcements of some pinch points in the network.

The EWIS study [EWIS, 2010] identified 29 potential cross-border reinforcements (almost half of them for offshore) with an indicative capital cost of €12.3 billion. The cost of network developments currently planned - primarily in order to accommodate the additional wind power between 2008 and 2015 - were estimated between €25 and €121 per installed kW of wind power capacity. €121 kW of wind power capacity represents around €4/MWh (wind energy) which is similar to the additional operational costs for addressing the added variability by wind power and is small compared to consumer prices and the overall benefits of wind generation.

EWIS used a market model in a year-round analysis to identify two particular critical points in time: a High Wind North and a High Wind South situation. In High Wind North, loop flows occur in and around Germany above all. As a consequence, specific capacity enhancement measures like dynamic line rating have been identified, as have phase shifting transformers. In its dynamic models for analyzing the impact on the network, EWIS assumed that the wind power plants have capabilities (such as active and reactive power, fault ride-through) that match the grid connection features required today in areas with high wind penetration.

Economic analysis of EWIS showed that the costs of the various transmission upgrade measures proposed are outweighed by the benefits brought about by the reinforced European network. EWIS’ recommendations are being used by ENTSO-E as a constituting element of the future network planning – for example in their first Ten Year Network Development Plan.

The EWIS study concluded that the wind power capacity assumed for 2015 can be integrated into the European power systems by addressing specific “pinch points” in the network with the appropriate reinforcement measures.

Since 2009, the planning of transmission upgrades at European level has been entrusted to ENTSO-E. This planning process must be transparent and carried out in close consultation with the various stakeholders – which include the wind energy sector and EWEA. The planning process is supervised by the European regulators (ACER) to ensure consistency with national network development plans. One of the vehicles of the consultation process is a document that ENTSO-E has to provide on a regular basis (every two years as of March 2012), containing a comprehensive vision of the expected and necessary Europewide transmission development, namely the Ten Year Network Development Plan 2010 (TYNDP). ENTSO-E issued a first “pilot” release of this TYNDP in June 2010 [ENTSO-E, 2010].

The TYNDP also points out what new transmission infrastructure can be used with sustainably mature new technologies, as well as providing long-term visions from both TSOs and stakeholders up to 2050 (including Smart grids and the Supergrid). The modelling of integrated networks in the TYNDP builds on inputs and results of the EWIS study [EWIS, 2010] in order to assess the most probable power flow patterns. The plan contains an identification of investment gaps and investment projects, particularly with respect to the development of cross-border capacities. With respect to the integration of offshore wind power, the Plan links to the work of the EU coordinator for “Connection of offshore wind power in Northern Europe”.

The document is of strategic importance because of its links with the European policy framework. It should be a basis for further input and discussions by regulators towards clarification of the cost allocation aspects for new infrastructure and cost recovery via tariffs for projects of European interest, regional projects and national projects.

The aim behind the 2010 Pilot version of the TYNDP was to be the first plan for Europe that was put together in a structured way and not just by assembling projects planned by each TSO. However this has not been fully achieved in the pilot version which does not yet (mid 2010) include the 2020 energy policy goals, or the Member States’ mandatory renewable energy targets.

# Recommendations to EU-27 member states

|  |  |
| --- | --- |
| Total lead times | * Reduce the average total lead time in the EU to 24 months * Make clear requirements on Environmental Impact Assessments (EIAs) (fixed deadlines, how many EIAs need to be carried out depending on the size of the park, its location) and reduce the number of irrelevant documents * Develop spatial planning by defining the most appropriate locations and wind development areas, lowering investment risks and streamlining project application procedures * Train and allocate enough civil servants to handle the expected applications |
| Number of authorities to be contacted directly and indirectly | * Develop and implement the ‘one-stop-shop’ approach in all member states * The authorities should disseminate clear information to developers on the administrative procedures and decision-making processes |
| Administrative lead times | * Lower the average administrative lead time to a maximum of 20 months, to ensure that the total lead time in the EU stays below 24 months * Perform onshore and offshore spatial planning and define the most suitable wind development areas, with streamlined administrative procedures in these areas * Provide clear definitions of the administrative requirements, in terms of procedures, deadlines and EIA content * Set deadlines for the administrative process. If the authority is not able to meet the deadline, the project automatically goes to the next stage * Train and allocate the necessary civil servants to handle the expected applications |
| Administrative costs | * Lower the average administrative costs in the EU to 1.5% of the total project costs * Perform a preliminary environmental assessment * Give incentives to competent authorities to gather data and studies collected under the EIA process and make them public * Limit the administrative requirements to the key relevant elements, in particular the ones identified through past projects. Update procedures regularly * Learn from past projects, and avoid requiring similar information from other projects with the same conditions * For offshore, maritime spatial planning should give special importance to crossborder cooperation and to developing synergies with other sea users |

# Glossary

ACTIVE POWER

Is a real component of the apparent power, usually expressed in kilowatts (kW) or megawatts (MW), in contrast to REACTIVE POWER (UCTE).

ADEQUACY

A measure of the ability of the power system to supply the aggregate electric power and energy requirements to the customers within component ratings and voltage limits, taking into account planned and unplanned outages of system components. Adequacy measures the capability of the power system to supply the load in all the steady states in which the power system may exist considering standards conditions (CIGRE definition).

ANCILLARY SERVICES

Are Interconnected Operations Services identified as necessary to perform a transfer of electricity between purchasing and selling entities (TRANSMISSION) and which a provider of TRANSMISSION services must include in an open access transmission tariff (UCTE).

CAPACITY

Is the rated continuous load-carrying ability of generation

CAPACITY FACTOR

(load factor) Is the ratio between the average generated power in a given period and the installed (rated) power.

CAPACITY VALUE

Also denoted as CAPACITY CREDIT of installed wind power capacity measures the amount of conventional generation that can be replaced by wind power capacity while maintaining existing level of supply security.

CONTINGENCY

Is the unexpected failure or outage of a system component

CONTROL AREA

Is a coherent part of the ENTSO-E INTERCONNECTED SYSTEM (usually coincident with the territory of a company

CONTROL BLOCK

Comprises one or more CONTROL AREAS, working together in the SECONDARY CONTROL function, with respect to the other CONTROL BLOCKS of the SYNCHRONOUS AREA it belongs to (UCTE).

CURTAILMENT

Means a reduction in the scheduled capacity or energy delivery (UCTE).

DYNAMIC LINE RATING

Controlled adaptation of transmission line rating as a function of continuously measured line temperature.

GATE CLOSURE

Is the point in time when generation and demand schedules are notified to the system operator.

INERTIA

Of a power system is the sum of all rotating mass inertias of the connected generation opposing a change of system frequency. The rotational speed of synchronous generators is an exact representation of the system frequency. In the very first moments after loss of generation the inertia of the rotating machinery helps to keep the system running.

INTERCONNECTED SYSTEM

An INTERCONNECTED SYSTEM is a system consisting of two or more individual electric systems that normally operate in synchronism and are physically connected via TIE-LINES, see also: SYNCHRONOUS AREA (UCTE).

INTERCONNECTION

An INTERCONNECTION is a transmission link (e.g. TIE-LINE or transformer) which connects two CONTROL AREAS (UCTE).

LOAD

Means an end-use device or customer that receives power from the electric system. LOAD should not be confused with DEMAND, which is the measure of power that a load receives or requires. LOAD is often wrongly used as a synonym for DEMAND (UCTE).

N-1 CRITERION

The N-1 CRITERION is a rule according to which elements remaining in operation after failure of a single network element (such as transmission line / transformer or generating unit, or in certain instances a bus bar) must be capable of accommodating the change of flows in the network caused by that single failure (UCTE).

N-1 SAFETY

Means that any single element in the power system may fail without causing a succession of other failures leading to a total system collapse. Together with avoiding constant overloading of grid elements, (N-1)-safety is a main concern for the grid operator.

NET TRANSFER CAPACITY

Maximum value of generation that can be wheeled through the interface between the two systems, which does not lead to network constraints in either system, respecting technical uncertainties on future network conditions.

POW ER CURVE

Relationship between net electric output of a wind turbine and the wind speed measured at hub height on 10 min average basis.

PRIMARY CONTROL

Maintains the balance between GENERATION and DEMAND in the network using turbine speed governors. PRIMARY CONTROL is an automatic decentralized function of the turbine governor to adjust the generator output of a unit as a consequence of a FREQUENCY DEVIATION / OFFSET in the SYNCHRONOUS AREA: PRIMARY CONTROL should be distributed as evenly as possible over units in operation in the SYNCHRONOUS AREA.

PRIMARY CONTROL RESERVE

It is the (positive / negative) part of the PRIMARY CONTROL RANGE measured from the working point prior to the disturbance up to the maximum PRIMARY CONTROL POWER (taking account of a limiter). The concept of the PRIMARY CONTROL RESERVE applies to each generator, each CONTROL AREA / BLOCK, and the entire SYNCHRONOUS AREA (UCTE).

PX

Is a Power Exchange Scheduling Coordinator, and is independent of System Operators and all other market participants.

REACTIVE POWER

Is an imaginary component of the apparent power. It is usually expressed in kilo-vars (kVAr) or mega-vars (MVAr). REACTIVE POWER is the portion of electricity that establishes and sustains the electric and magnetic fields of alternating current equipment. REACTIVE POWER must be supplied to most types of magnetic equipment, such as motors and transformers and causes reactive losses on transmission facilities. REACTIVE POWER is provided by generators, synchronous condensers, or electrostatic equipment such as capacitors, and directly influences the electric system voltage. The REACTIVE POWER is the imaginary part of the complex product of voltage and current (UCTE).

RELIABILITY

Describes the degree of performance of the elements of the bulk electric system that results in electricity being delivered to customers within accepted standards and in the amount desired. RELIABILITY on the transmission level may be measured by the frequency, duration, and magnitude (or the probability) of adverse effects on the electric supply / transport / generation. Electric system RELIABILITY can be addressed by considering two basic and functional aspects of the electric system: Adequacy — The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements. Security — The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements (UCTE).

SECONDARY CONTROL

Is a centralized automatic function to regulate the generation in a CONTROL AREA based on SECONDARY CONTROL RESERVES in order to maintain its interchange power flow at the CONTROL PROGRAM with all other CONTROL AREAS (and to correct the loss of capacity in a CONTROL AREA affected by a loss of production) and, at the same time, (in case of a major FREQUENCY DEVIATION originating from the CONTROL AREA, particularly after the loss of a large generation unit) to restore the frequency in case of a FREQUENCY DEVIATION originating from the CONTROL AREA to its set value in order to free the capacity engaged by the PRIMARY CONTROL (and to restore the PRIMARY CONTROL RESERVES).

SECURITY LIMITS

Define the acceptable operating boundaries (thermal, voltage and stability limits). The TSO must have defined SECURITY LIMITS for its own network. The TSO shall ensure adherence to these SECURITY LIMITS. Violation of SECURITY LIMITS for prolonged time could cause damage and/or an outage of another element that can cause further deterioration of system operating conditions (UCTE).

STABILITY

Is the ability of an electric system to maintain a state of equilibrium during normal and abnormal system conditions or disturbances.

STATIC LOAD FLOW CALCULATIONS

Investigate the risk of system overload, voltage instability and (N-1)-safety problems. System overload occurs when the transmitted power through certain lines or transformers is above the capacity of these lines/transformers. System static voltage instability may be caused by a high reactive power demand of wind turbines. Generally speaking, a high reactive power demand causes the system voltage to drop.

SYNCHRONOUS AREA

Is an area covered by INTERCONNECTED SYSTEMS whose CONTROL AREAS are synchronously interconnected with CONTROL AREAS of members of the association. Within a SYNCHRONOUS AREA the SYSTEM FREQUENCY is common on a steady state. A certain number of SYNCHRONOUS AREAS may exist in parallel on a temporal or permanent basis. A SYNCHRONOUS AREA is a set of synchronously INTERCONNECTED SYSTEMS that has no synchronous interconnections to any other INTERCONNECTED SYSTEMS, see also: UCTE SYNCHRONOUS AREA (UCTE).

SYSTEM FREQUENCY

Is the electric frequency of the system that can be measured in all network areas of the SYNCHRONOUS AREA under the assumption of a coherent value for the system in the time frame of seconds (with minor differences between different measurement locations only) (UCTE).

TERTIARY CONTROL

Is any (automatic or) manual change in the working points of generators (mainly by re-scheduling), in order to restore an adequate SECONDARY CONTROL RESERVE at the right time (UCTE). The power which can be connected (automatically or) manually under TERTIARY CONTROL, in order to provide an adequate SECONDARY CONTROL RESERVE, is known as the TERTIARY CONTROL RESERVE or MINUTE RESERVE. This reserve must be used in such a way that it will contribute to the restoration of the SECONDARY CONTROL RANGE when required; The restoration of an adequate SECONDARY CONTROL RANGE may take, for example, up to 15 minutes, whereas TERTIARY CONTROL for the optimization of the network and generating system will not necessarily be complete after this time (UCTE).

TRANSIENT STABILITY

The ability of an electric system to maintain synchronism between its parts when subjected to a disturbance of specified severity and to regain a state of equilibrium following that disturbance (UCTE).

TRANSMISSION SYSTEM OPERATOR

Is a company that is responsible for operating, maintaining and developing the transmission system for a CONTROL AREA and its INTERCONNECTIONS (UCTE).

# Abbreviations

AC

Alternating Current

ACER

Agency for Coordination of Energy Regulation

CAES

Compressed Air Energy Storage

CHP

Combined Heat and Power

DFIG

Doubly Fed Induction Generator

DG

Distributed Generation

DSM

Demand Side Management

DSO

Distribution System Operator

EEX

European Energy Exchange

EEZ

Exclusive Economic Zone (offshore)

ENTSO-E

European Network for Transmission System Operators for Electricity

ERGEG

European Regulators for Energy and Gas

EU

European Union

EUA

European Union Allowances

EU ETS

European Emission Trading Scheme

EUR

Euro

EWIS

European Wind Integration Study

FACT

Flexible AC Transmission System Device

FRT

Fault Ride Through

GGCF

Generic Grid Code Format

GHG

Greenhouse Gases

GW

Gigawatt

GWh

Gigawatt hour

HVAC

High voltage AC

HVDC

High voltage DC

HVDC CSC

High voltage DC with Current Source Converters

HVDC LCC

High voltage DC with Line Commutated Converters

HVDC VSC

High voltage DC with Voltage Source Converters

ICT

information and communication technology

IEC

International Electrotechnical Committee

IGBT

Insulated Gate Bipolar Transistor

ISO

Independent System Operator

IPP

Independent Power Producer

KWh

Kilo Watt Hour

LCC

Line Commutated Converter

MIBEL

Mercado Ibérico de Electricidade (Iberian Electricity Market)

MOE

Merit Order Effect

MVAR

Mega Volt Ampere Reactive

MW

Megawatt

MWh

Megawatt hour

RE

Renewable Energy

RES

Renewable Energy Sources

NRMSE

Normalized Root Mean Square Error

NTC

Net Transfer Capacity

NWP

Numerical Weather Prediction

OTC

Over-The-Counter Markets

PAC

Pumped Hydro Accumulation Storage

PMSG

Permanent Magnet Synchronous Generator

RMSE

Root Mean Square Error

SAF

System Adequacy Forecast

SCADA

Supervisory Control and Data Acquisition

SCIG

Squirrel Cage Induction Generator

SVC

Static Var Compensator

TEN-E

Trans-European Networks Energy

TSO

Transmission System Operator

TW

Terawatt

TWh

Terawatt hour

TYNDP

Ten Year Network Development Plan

UCTE

(previous) Union for the Coordination of Transmission of Electricity (presently dissolved into ENTSO-E)

VPP

Virtual Power Plant

VSC

Voltage Source Converter

WAMS

Wide Area Monitoring System

WEPP

Wind Energy Power Plant

WRIG

Wound Rotor Induction Generator