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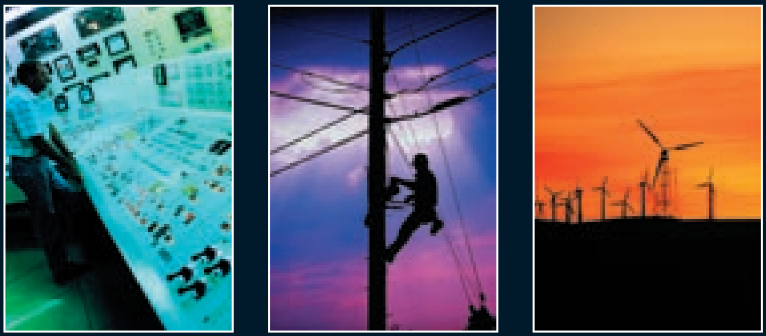

LARGE SCALE INTEGRATION OF WIND ENERGY IN THE EUROPEAN POWER SUPPLY: analysis, issues and recommendations

A report by EWEA

RATIONALE

1. *We now live in an era of energy uncertainty. The days of cheap and abundantly available energy are over.*

2. *Europe is running out of indigenous energy resources in the form of fossil fuels at a time when a paradigm shift in energy prices is occurring. It is clear that this century will be characterised by intensified competition for energy which will inevitably push up prices, lead to periodic scarcity and precipitate a scramble for reserves among the world's main economic blocks.*

3. *Europe's dependency on imported fossil fuel has become a threat to economic stability because of the impact of increased fuel prices on the cost base, most notably on the price of electricity. It is essential that Europe develops its own internal energy resources to the maximum extent possible, as well as promoting energy efficiency.*

4. *Europe is an energy intensive region heavily reliant on imports; already today, it imports 50% of its energy needs and that share is likely to increase to 70% within two decades unless Europe changes direction. By 2030, oil imports would rise from 76% to 88% and gas imports from 50% to 81%, compared to 2000. Indigenous fossil fuel resources, such as the North Sea, are in rapid decline.*

5. *Europe is the world leader in renewable energy and in the most promising and mature renewable technology, wind power, it has both a competitive and comparative advantage.*

6. *Wind energy will not only be 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 forms of commercial benefits, technology research, exports and employment.*

7. *The economic future of Europe can be planned on the basis of known and predictable cost of electricity derived from an indigenous energy source free of all the security, political, economic and environmental disadvantages associated with oil and gas.*

8. *There is an urgent need to address inefficiencies, distortions and historically determined institutional and legal issues related to the overall structure, functioning and development of the broader European electricity markets and power infrastructure.*

9. *The Commission has concluded that current electricity markets are not competitive for four main reasons: lack of cross-border transmission links; existence of dominant, integrated power companies; biased grid operators; low liquidity in wholesale electricity markets. These four barriers are also the main institutional and structural deficiencies preventing new technologies such as wind power to enter the market.*

10. *The major issues of wind power integration are related to: changed approaches in operation of the power system, connection requirements for wind power plants to maintain a stable and reliable supply, extension and modification of the grid infrastructure, and influence of wind power on system adequacy and the security of supply.*

11. *The need for infrastructure investments is not based on wind energy only; consequently, grid extensions, grid reinforcement and increased backup capacity benefit all system users. An integrated approach to future decisions is needed.*

12. *A large contribution from wind energy to European power generation is feasible in the same order of magnitude as the individual contributions from the conventional technologies.*

14. *The capacity of European power systems to absorb significant amount of wind power is determined more by economics and regulatory rules than by technical or practical constraints. Already today a penetration of 20% of power from wind is feasible without posing any serious technical or practical problems.*

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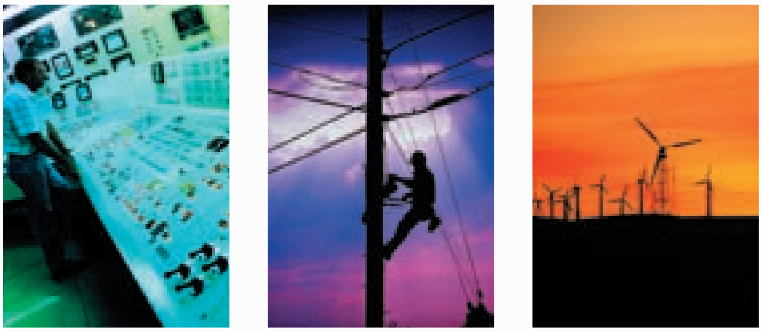

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Foreword

Wind power is ready to be a mainstream energy supply technology across Europe.

One of the core challenges for wind power to contribute to the European energy supply at a penetration level comparable to that of conventional power sources, is how to effectively integrate significant amounts of wind power into European electricity systems.

The detailed analysis of the technical, economic and regulatory issues, which need to be addressed to move Europe towards a more secure energy future through increased wind power production, is contained in the EWEA report: *"Large scale integration of wind energy in the European power supply : analysis, issues and recommendations"*, (December 2005).

The analysis, conclusions and recommendations are based on a review of over 180 sources - published data, reports, research findings from all stakeholders across the power industry, operators, utilities and experts. This report is the most comprehensive and up-to-date assessment of the topic of large scale integration of wind energy in Europe.

The Executive Summary here presents the main findings of the report, its rationale, conclusions and recommendations.

Frans Van Hulle,
Technical Director, EWEA

Executive Summary

1. Background

Turning the energy challenge into a competitive advantage

Europe stands out in a global context as an energy intensive region heavily reliant on imports. Today, we are importing 50% of our energy needs and that share is likely to increase to 70% two decades from now unless Europe changes direction. Most of our oil comes from the Middle East and virtually all of our gas from just three countries: Russia, Algeria and Norway. Our economy is relying on the ready availability of hydrocarbons at affordable prices. Europe is running out of indigenous energy resources in the form of fossil fuels at a time when a paradigm shift in energy prices is occurring. Most observers agree that the era of cheap fuels is over and signs are emerging that competition for ownership of oil and gas is becoming fiercer and will intensify heavily in the coming years. The era of energy uncertainty has come.

It is clear that this century will be characterised by intensified competition for energy, which will inevitably push up prices, lead to periodic scarcity and precipitate a scramble for reserves among the world's main economic blocks. The continued economic and social progress of regions like Europe will depend in the short term on their ability to compete robustly for existing fossil fuels and, in the longer run, on their ingenuity in developing new energy sources which are independent of international competition and benign for the environment.

The cost of crude oil has doubled within the past two years from $25/bbl to $50/bbl, and a new peak of $70.85/bbl was reached in August 2005. The price of gas has followed the same trend which has a fundamental impact on the cost of generating electricity in Europe. It is clear that world oil and gas prices have risen much more quickly than anticipated, and it is evident that the EU dependency on imported fossil fuel has become a threat to economic stability because of the impact of increased fuel prices on the cost base, most notably on the price of electricity. Forecasts of economic growth are being revised downwards as the impact of higher fuel prices strengthens. The level of fuel risk in electricity systems has increased. In the era of low fossil fuel prices, this strategy delivered cheap electricity, but in an era of high fuel prices it can only deliver expensive electricity.

In its Green Paper on Security of Energy Supply in 2000, the Commission warned that the EU had a *"structural weakness regarding energy supply"* and stated that the EU *"must take better charge of its energy destiny."* The Commission baseline scenario highlighted that, by 2030, oil imports would rise from 76% to 88% and gas imports from 50% to 81%, compared to 2000. Indigenous fossil fuel resources, such as the North Sea, are in rapid decline and dependency on imports is correspondingly increasing.

It is essential that Europe develops its own internal energy resources to the maximum extent possible, as well as promotes energy efficiency. Europe is a world leader in renewable energy and in the most promising and mature renewable technology, wind power, it has both a competitive and comparative advantage. In 2004, European wind turbine manufacturers had a global market share of more than 80%. Wind energy will not only be 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 forms of commercial benefits, technology research, exports and employment. Without reliable, sustainable, and reasonably priced energy there can be no sustainable long-term growth and Europe will become economically disadvantaged.

The fact that the wind power source is free and clean is, of course, economically and environmentally significant but the more fundamental point at issue is that the cost of the electricity is fixed, once the plant has been built. The long-term implication is that the economic future of Europe can be planned on the basis of known and predictable cost of electricity, derived from an indigenous energy source free of all the security, political, economic and environmental disadvantages associated with oil and gas.

Wind power and European electricity

According to the International Energy Agency (IEA), the European Union will invest €100 billion in transmission networks and €340 billion in distribution networks for reinforcement, asset replacements and new connections over the three decades from 2001 to 2030. **Irrespective of whatever policy is chosen by the EU, massive investments in generation plants and grids are required.** For policy-makers, the question is the priority to be assigned to different fuels. The vision presented here is that wind power meets all the requirements of current EU energy policy and simultaneously offers a way forward in an era of high fuel prices.

Wind energy technology has made major progression since the generation of wind turbines from the early 1980s. Twenty five years of technological progress have resulted in today's wind turbines being a state-of-the-art modern technology - modular and quick to install. At a given site, a single modern wind turbine annually produces 180 times more electricity and at less than half the cost per kWh than its equivalent twenty years ago. The wind power sector includes some of the world's largest energy companies. **Effective regulatory and policy frameworks have been developed and implemented, and Europe is the undisputed world leader in wind energy.**

Wind provides less than 3% of European power needs, but is capable of delivering 12% by 2020 and in excess of 20% by 2030. Such penetration levels, however, will require that decision makers and stakeholders in the electricity sector work together to make the necessary changes to the grid infrastructure in Europe, which has been constructed and operated in the last century with large centralised coal, hydro, nuclear and, more recently, gas fired power plants in mind.

Wind power is disadvantaged compared to the situation under which conventional power sources such as oil, gas, coal and nuclear power sources were developed and introduced. Until the 1980s, electricity generation, distribution, grid reinforcement, grid extensions, and electricity selling were undertaken by national, vertically integrated monopolies, which were granted exclusive rights and mandates to finance investments and research in new capacity and technologies through state subsidies and levies on electricity bills. As Europe is moving in the direction of more liberalised power markets, those options are no longer available and new technologies are facing a more challenging environment on the path to market penetration and maturity. Meanwhile, public funding for energy research and development is being drastically reduced. Over the last three decades, worldwide, 92% of all R&D funding (€227 billion) has been spent on non-renewables – largely fossil fuels and nuclear technologies – compared to €19 billion for all renewable energy technologies.

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2. Overview

In 2000, when fuel prices were far lower than today, the European Commission's Green Paper on Security of Supply recognised the potential of renewable energy sources:

"Renewable sources of energy have a considerable potential for increasing security of supply in Europe. Developing their use, however, will depend on extremely substantial political and economic efforts. [...] In the medium term, renewables are the only source of energy in which the European Union has a certain amount of room for manoeuvre aimed at increasing supply in the current circumstances. We can not afford to neglect this form of energy."

It continued:

"Effectively, the only way of influencing [European energy] supply is to make serious efforts with renewable sources."

In 2003, the European Commission estimated that wind energy will be the main contributor to meeting the 2010 targets for renewable electricity in the European Union.

One of the core challenges for wind power to contribute to the European power mix at a penetration level comparable to that of the conventional power sources is how to effectively integrate significant amounts of wind energy into the European electricity systems. More specifically, this report analyses the technical, economic and regulatory issues that need to be addressed to move Europe towards a more secure energy future through increased wind power production.

Observing comments from some electricity sector stakeholders and policy makers, one could get the impression that wind power is a "grid trouble-maker" and that wind power constitutes the greatest technical challenge the European power system has ever had to face. *Wind power is unreliable; wind power cannot to any significant degree contribute to European electricity production; wind power threatens the safe operation of the electricity grids; what happens when the wind stops blowing?*

The "intermittency " myth

Wind power is sometimes incorrectly described as an intermittent energy source. This is misleading because, on a power system level, wind power does not start and stop at irregular intervals, which is the meaning of intermittent. **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 are influenced by a large number of planned and unplanned factors. The changing weather makes millions of people switch on and off heating, lighting, e.g. a sudden thunderstorm. 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, which particularly impacts hydro and nuclear energy. Trees fall on power lines, or are iced up and cause sudden interruptions of supply.

The system operators need to balance out planned and unplanned changes in 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 one of variability or intermittency per se, but how to predict, manage and ameliorate variability and what tools can be utilised 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.

Wind power in the system should not be analysed in isolation

Wind cannot be analysed 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 aspects determining the system's capability of accommodating a high 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 electricity system.

Grid operators do not have to take action every time an individual consumer changes his or her consumption, e.g. 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.**

Furthermore, wind power has to be considered relative to the overall demand variability and the variability and intermittency of other power generators.

The variability of the wind energy resource is important to consider only 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 somewhere – it is always 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.

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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 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 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 a thousand MW – that is true intermittency.** Power systems have always had to deal with these sudden output variations of large power plants as well as the variable demand. The procedures put in place can be applied - and in some countries they are - to deal with variations in wind power production as well.

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 the shut-down of a 2 MW wind turbine. It will have to respond to the shut-down of a 500 MW coal fired plant or a 1,000 MW nuclear plant instantly.

The 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 rules than by technical or practical constraints.**

It is more accurate to state that larger scale penetration of wind does face barriers; not because of its variability but because of a series of market barriers in electricity markets that are neither free or fair, coupled with a classic case of new technologies threatening old paradigm thinking and practice.

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.

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Large-scale grid integration of wind power

For small penetration levels of wind power in a system, grid operation will not be affected to any significant extent. Wind power supplies less than 3% of overall EU electricity demand but there are large regional and national differences.

The already established control methods and backup available for dealing with variable demand and supply are more than adequate for dealing with the additional variable supply such as wind power at penetration levels up to around 20% of gross demand, depending on the nature of a specific system. For larger penetration levels, some changes may be needed in power systems and their methods of operation to accommodate the further integration of wind energy.

In Denmark, the country in the world with the highest penetration of wind power, 21% of total consumption was met with wind power in 2004. **In the west-Denmark transmission system, which is not connected to the eastern part of the country, some 25% of electricity demand is met by wind power in a normal wind year** and, on some occasions, the wind has been able to cover 100% of instantaneous demand.

The integration of large amounts of wind power is often dismissed as impossible and many grid operators are reluctant to make changes in long established procedures to accommodate wind power. In Denmark, the grid operator was initially sceptical about how much wind power the system could cope with. The attitude of many grid operators to wind power can best be illustrated by the following quote from Eltra, the TSO in west-Denmark, at the presentation of its annual report.

"Since the end of 1999 - so in just three years - wind power capacity in the Jutland-Fyn system has increased from 1,110 MW to 2,400 MW. In installed capacity that is twice the capacity of the «Skydstrup» power Plant near Aarhus. Seven or eight years ago, we said that the electricity system could not function if wind power increased above 500 MW. Now we are handling almost five times as much. And I would like to tell the Government and the Parliament that we are ready to handle even more, but it requires that we are allowed to use the right tools to manage the system».

In the western Energinet (formerly Eltra's) supply area, wind energy covers some 25% of electricity demand in a normal wind year and it is not a technical problem to handle more – it is a regulatory issue. The tools for managing more wind power in the system are developed and grid operators should be allowed to use them.

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

In those areas of Europe where wind power development is still in its initial stage, many lessons can be learned from Denmark, Germany and Spain. However, it is important that stakeholders, policy makers and regulators in those emerging markets realise that the issues that TSOs in those three countries are faced with will not become an issue until much larger amounts of wind power are connected to the national grids.

One of the biggest mistakes in parts of the public debate about integrating wind power is that it is treated in isolation. Wind power has distinct technical features just like any other electricity generation source. Nuclear power and some of the gas and coal-fired power plants are very inflexible and are maintained at constant generation level. Seen in isolation, this is an undesirable feature because electricity demand varies significantly and constantly throughout the day. Other coal and gas plant, and hydro, are more flexible and outputs can be changed more rapidly. Integrating wind power has other distinct features. The point is that no technology, neither "base load" nuclear power nor variable production wind power, should be dealt with in isolation. It is the combined effects of all technologies, as well as the demand patterns, that matters for grid operators.

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The European Dimension

There is an urgent need to address inefficiencies, distortions and historically determined institutional and legal issues related to the overall structure, functioning and development of the broader European electricity markets.

A re-orientation in the European power systems to take the characteristics of large-scale wind power into account is technically and economically feasible, and in line with overall European objectives.

The major issues of wind power integration are related to changed approaches in operation of the power system, connection requirements for wind power plants to maintain a stable and reliable supply, extension and modification of the transmission infrastructure. More cross-border links - interconnectors - will enable collection of wind power from resourceful onshore and offshore areas and make optimal use of geographical aggregation, and solve institutional and legal barriers to increased wind power penetration. Conclusions on these issues are presented below.

Before the 1980s, electricity generation, distribution, enforcement, grid expansion and selling were undertaken by national, vertically integrated monopolies that were granted exclusive rights. This historic legacy of the European power sector continues to influence the possibility to develop and integrate new technologies into the power mix. In the 1990s, the European Commission challenged the existence of such monopolies as being contrary to the Treaty's rules on the free movement of goods. This eventually resulted in the adoption in 1996 of the first electricity Directive and the first Directive on gas in 1998.

Following the adoption of the 1997 Treaty of Amsterdam, the European Union bases its energy policy on three core principles, namely:

- **Environmental protection** – in both energy production and energy use to maintain ecological and geophysical balances in nature;
- **Security of Supply** – which aims to minimise risks and impacts of possible supply disruption;

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- **Competitive energy systems** - to ensure low cost energy for producers and consumers.

Furthermore, the growing import dependence of European energy supply, with its associated risk of economic disruptions, is a growing concern and measures to reduce it and increase indigenous energy production are needed.

Since 2001, the Commission has monitored the development of market opening through the Benchmarking Reports on the Implementation of the Internal Electricity and Gas Markets. In its fourth Benchmarking report, published in January 2005, the European Commission warns that governments must do more to open up electricity and gas markets.

The Commission points out four key reasons for the lack of success in achieving a competitive market:

- **Lack of cross-border transmission links**
- **Existence of dominant, integrated power companies**
- **Biased grid operators, and**
- **Low liquidity in wholesale electricity markets**

From the European Commission's point of view, the electricity grid and the structure of the power sector are the main stumbling blocks to effective competition in the European electricity markets. It sees market concentration and dominant incumbents as *"the most important obstacle to the development of vigorous competition"*.

Further, it notes that *"the internal energy market will need to develop in a manner consistent with the Community's sustainability objectives. This means that the necessary incentives to support the penetration of renewables, the reduction of emissions and demand management need to be maintained."*

The four main barriers outlined above are not only barriers to creating effective competition in European power markets, they are also the main institutional and structural deficiencies preventing new technologies such as wind power to enter the market.

Increased cross-border transmission is a precondition for effective competition. It will also reduce the cost of integrating wind power on a large scale dramatically and reap substantial "geographic spread" benefits of variable output wind generation.

Besides reducing the aggregated variability of wind power, the direct benefit of geographical aggregation of wind power output is the increased amount of firm electricity which can be used to retire conventional power plant.

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3. Conclusions

A large contribution from wind energy to European power generation is technically and economically feasible, in the same order of magnitude as the individual contributions from the conventional technologies developed over the past century. These large shares can be realised while maintaining a high degree of system security, and at modest additional system costs. However, some redesigning of the power systems, including their methods of operation, is needed. The report details that the constraints of increasing wind power penetration are not inherently technical problems with wind technology per se. The barriers are mainly a matter of regulatory, institutional and market modifications, and should be dealt with in a broader power market context.

The major issues of wind power integration are related to changed approaches in operation of the power system, connection requirements for wind power plants to maintain a stable and reliable supply, extension and modification of the grid infrastructure, and influence of wind power on system adequacy and the security of supply. Finally, institutional and legal barriers to increased wind power penetration need to be addressed and overcome. Conclusions on these issues are presented below.

System operation: power and energy balancing

The possibilities and detailed strategies for managing variable-output wind power vary between national and regional power systems. Like any other form of generation, wind power will have an impact on power system reserves. It will also contribute to a reduction in fuel usage and emissions. The impact of wind power depends mostly on the wind power penetration level, but also depends on the power system size, generation capacity mix, the degree of interconnection to neighbouring systems and load variations.

Large power systems can take advantage of the natural diversity of variable sources. **A large geographical spread of wind power will reduce variability, increase predictability and decrease the occurrences of near zero or peak output.** Power systems have flexible mechanisms to follow the varying load and plant outages that cannot always be accurately predicted. The same mechanisms are used to integrate wind power with its characteristic fluctuations. Wind farms have the inherent advantage over conventional power plants of being smaller in total output capacity. On the wind farm level, their power output variation is always smaller than, for example, the variation caused by an outage of a conventional plant. On regional aggregated level, wind power variations are smoothed and the occurrences of zero wind power are rare.

On the second to minute time scale, wind power has very little if no impact on the reserves (primary reserve). This is because the large number of individual turbines will have their second-to-second variations uncorrelated and it will smooth out, together with the load variations.

On the 10 minute to hour time scale wind power will affect the (secondary) reserves when the magnitude of wind power variations becomes comparable to the load variations. When about 10% of total electricity consumption is produced by wind power, the increase in reserves is calculated for various national countries and regions to 2-4% of installed wind power capacity, assuming proper use of forecasting techniques.

On time scale of hours to days, wind power will affect the scheduling of conventional power plants. On this time scale the impacts of wind power are dependent on forecast accuracy as well as on how flexible the conventional power producers in the system area are.

Accurate methods for short-term forecasting of wind power are widely available as there is a whole range of commercial tools and services in this area, covering a wide range of applications and customised implementation.

On an annual basis, reducing the forecast horizon from day-ahead to a few hours ahead reduces the required balancing energy due to prediction errors by 50%.

Wind energy is thus variable but predictable. Predictability favours the economic balancing of wind power in the system together with the fluctuations of electrical demand and other power generation sources, especially at wind power penetrations above 5%. The predictability qualities of wind energy must be analysed in a directly comparable way to that adopted for conventional plant which is not variable but is intermittent since large generating sets can be and are lost in an entirely unpredictable manner.

Balancing solutions as of today mostly involve existing conventional generation units (thermal and hydro). Other solutions for managing increased variability in the power systems include load management, interconnection and energy storage.

New technology and innovation enable wind farms of today to function as (virtual) power plants with the capability of delivering a range of grid supporting services, such as frequency and voltage control. Whereas not necessary at low penetrations, these advanced wind farm properties will prove to be increasingly useful at high levels of wind power penetration.

Grid codes and excessive technical requirements

It is evident that clear rules are needed to ensure that the power system keeps operating well and safely when generators are connected. In this respect the wind energy technology is developing to keep up with ever stricter technical requirements. There are however continuous changes of grid codes, technical requirements and related regulation, often introduced on very short notice and with minimum involvement of the wind power sector.

Grid codes and other technical requirements should reflect the true technical needs for system operation and should be developed in cooperation between TSOs, the wind energy sector and government bodies.

Present grid codes often contain very costly and challenging requirements (such as fault-ride through capability and primary control) that have no technical justification, e.g. because the level of wind power penetration is insignificant (i.e. in most areas of Europe).

They are often developed by vertically-integrated power companies, i.e. within companies in competition with wind farm operators, in highly non-transparent manners.

The technical grid code requirements and regulations vary considerably from country to country. The differences in requirements, besides local 'traditional' practices, are caused by different wind power penetrations and by different degrees of power network robustness.

It has been suggested to introduce harmonised grid codes for wind energy at a European level. In theory it could provide fewer burdens on the wind turbine manufacturers if each turbine model would not have

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to be adjusted for each market. However, it would be difficult to arrive at an all-encompassing European code for wind turbines because the technical requirements would have to reflect very different national conditions in terms of energy mix, interconnection, geographical size of the systems and wind power penetration levels. The immediate danger is that very strict requirements reflecting the technical needs in the few high wind penetration regions of Europe would be expanded to regions of Europe where such requirements have no technical justification and, thus, impose unnecessary cost on manufacturers as well as consumers in most European countries.

In any case, a harmonised grid code for wind power should be coordinated at EU level by an independent European regulator and/or the European Commission with the participation of the relevant stakeholders, including the wind turbine manufacturers. That said, it is difficult to comprehend why vertically-integrated power companies push so strongly for a European grid code for wind power when no harmonisation seems to be needed for other generating technologies.

As a rule, the power system robustness and penetration level and other generation technologies should be taken into account and an overall economically efficient solution should be sought. For example, it is more economic to provide primary and secondary control from conventional power plants, and wind farm operators should be demanded to provide such service only in cases where limits in existing reserves are foreseen for some critical situations. Another example of economic thinking would be to fulfil the requirement for reactive power by installing and controlling devices such as FACTS directly in the transmission network.

Costly technical requirements should only be applied if there is a true technical rationale for them and if their introduction is required for reliable and stable power system operation. The assessment of the need for requirements should be made by government bodies or TSOs that are fully separated, both legally and in terms of ownership, from any generation activities, to avoid biased decisions.

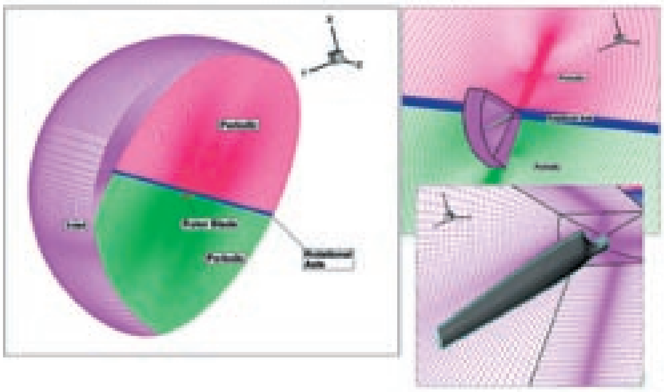
The wind turbine manufacturers are keen to establish a close working relationship with grid operators, customers and regulators to find acceptable compromises.

Besides the technical requirements, there is the issue of interconnection practice. There is a need for a transparent method to define the maximum interconnection capacity at a given network point as well as a definition of the maximum time for the TSO or DSO to perform relevant studies. Such method could ideally be defined by a neutral authority for example a regulator.

■ Dynamic system studies provide basis for improved connection practices of wind power

In general, from dynamic system studies carried out for various countries (Denmark, Germany, Spain) it is concluded that power systems dynamics are not a principal obstacle to increasing the penetration of wind power, provided that adequate measures are taken both in wind turbine technology design and in the operation and technology of the grid.

R&D: wind tunnel computer simulation



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R&D should continue to further improve the knowledge on dynamic interaction of system and wind power plants. Also, continued research work is needed to improve the dynamic models for the latest wind turbine types and for entire wind farms. Such modelling efforts become increasingly important because several TSOs have started to demand that wind farm developers submit a dynamic simulation model of the wind farm before granting connection permits. The models are used to carry out a dynamic grid integration assessment.

Grid upgrades and costs are not an isolated wind power issue

The grid infrastructure in Europe needs upgrading – on country, cross-border and trans-European levels – not only to accommodate increasing amounts of wind power cost efficiently, but also other power generating technologies. The IEA estimates that more than half of the new capacity required to meet rising electricity demand in the EU between 2001 and 2030 will be for gas. It is very rarely part of the public debate how adequate transmission and distribution is secured for the large additions of gas and coal power plant in Europe over the coming decades.

The need for infrastructure investments is obviously not arising exclusively from an increased use of wind power, which seems to be the underlying message from many market participants. **Consequently, grid extensions, grid reinforcement and increased backup capacity benefit all system users, not only wind power.** Furthermore, it is impossible to allocate the cost to individual projects or technologies. Therefore, it does not make sense to look at the future infrastructure challenges in the light of one single technology. It would be tantamount to making decisions on road building by only looking at the characteristics of bicycles, ignoring lorry and car traffic.

Wind power is not, and should not be, the only technology that benefits from improvements in the overall grid infrastructure and system operation. Therefore, an integrated approach to future decisions is needed which, of course, should take into account the specifics of wind power technology as well as the specifics of other technologies.

Grid extensions and reinforcements will benefit the whole power system and are a precondition for creating real competition in the emerging EU internal electricity market – a challenge currently being blocked by numerous distortions in the conventional power market such as the lack of effective unbundling of transmission and generation companies. Grids are natural monopolies and should be regulated as such, but this is presently not the case in most Member States.

The process of upgrading the grid systems is a very complex one and requires short-term and long-term measures to enable a smooth integration of wind power. Short-term measures include mainly optimisation of existing infrastructure, and so-called soft measures like adapted management procedures.

In the longer term, a European super-grid is proposed to accommodate large amounts of offshore wind power and to utilize continental-wide smoothing effects of wind power to a maximal extent, as well as to improve the functioning of the emerging internal electricity market. The wind is always blowing somewhere, smoothening fluctuations, and enabling more accurate short-term forecasts.

■ Improving cross-border transmission just by changing market rules

Cross-border transmission of wind power appears to be less of a technical issue than a trade and market issue. The problems wind power is facing presently are mainly caused by the fact that there is not yet a slot of cross-border capacity for variable-output power from renewables. Making such a slot available would enable cross-border trade in wind power according to internal electricity market principles.

While the European RES-E Directive makes it possible for Member States to grant priority dispatch for renewables in the national regulatory frameworks, there is no such notion as priority allocation of cross-border capacity for electricity from renewables. According to the principles of the internal electricity market, this allocation should be market-based, rather than historically determined.

Fuel replacement and capacity credit of wind power benefit security of supply.

Wind energy will replace energy produced by other power plants, which improves the energy adequacy of the power system. This is especially beneficial when wind is saving limited energy sources like hydro power and imported fuels like gas, coal and oil, decreasing the effect of price peaks on the national economy.

In addition to producing energy, wind power replaces conventional generating capacity. At low to moderate wind power penetration levels, its relative capacity credit is equal to the average wind power produced during times of peak demand (between 20% and 35% of installed onshore wind power capacity, depending on the site conditions). At higher wind power penetration levels, wind's relative capacity credit becomes lower than the average wind power output in times of peak demand.

In addition to the above, **adding wind power to the existing system is contributing favourably to the security of supply by virtue of technology diversification and indigenous production.**

The economic impacts of wind power integration are beneficial

■ Additional balancing costs for wind power

Comprehensive national studies have focused on determining the additional balancing costs as a function of increasing wind penetration in the national power system (Nordic region, Germany, UK, Ireland, Spain). Despite the differences in assumptions, optimisation criteria and system characteristics, the studies arrive at similar results. There is a gradual increase of the additional balancing costs with wind power penetration. **Because of the positive effect of geographical smoothing, results from these studies show that power systems in large geographical areas can integrate wind power at lower cost. Likewise, good interconnection to neighbouring systems reduces balancing costs.**

Both the allocation and the use of reserves cause extra system costs. This means that only the increased use of dedicated reserves, or increased part-load plant requirement, will cause extra costs. **According to several national studies made so far, there is no need for additional conventional plant and that extra reserve needs for wind power can be obtained from the existing conventional power plants.** Estimates regarding the costs of increase in secondary load following reserves suggest €1–3/MWh (of wind) for a wind power penetration of 10% of gross consumption and €2-4/MWh for higher penetration levels. The costs are quite sensitive to the accuracy of wind power forecasting, as well as the practice of applying forecasts in the market rules.

■ Additional network costs from national studies

A number of national studies (Austria, Denmark, Germany, France, Netherlands) have determined the additional grid reinforcement requirements and corresponding costs due to wind power. Such studies perform load flow simulations of the corresponding national transmission and distribution grids and take into account different scenarios of national wind integration, utilising the most favourable sites. These **country-specific studies (both in view of onshore and offshore) indicate that the grid extension/reinforcement costs caused by additional wind generation are in the range of €0.1 to €4.7/MWh wind, the higher value corresponding to a wind penetration of 30% in the system (UK).** When properly socialised in an unbundled market, these cost levels, as reflected in the end user price are low – even up to high wind penetrations.

■ Overall system economic effects

Generation costs constitute the largest fraction of the cost of power. Expected cost developments of wind power and conventional generation are such that **in a scenario with substantial amounts of wind power, the additional costs of wind power (higher installation costs, increased balancing, network upgrade) would be outweighed by the benefits.**

The expected continuing decrease of wind power generation costs (reduction of 20% for onshore and 40% offshore by 2020 as compared to 2003 levels) is an important factor. The economic benefit of wind becomes even larger when the social benefits of CO_2 emission reduction and other environmental benefits are taken into account.

Large national studies in UK, Germany and Denmark confirm that **system integration costs, under the most conservative assumptions (low gas price compare to the current level, low to zero social benefit of CO_2) are only a fraction of the actual consumer price of electricity** and are in the order of magnitude of €0 to €4/MWh (consumer level). It is recommended that similar studies are undertaken at European level.

In addition, wind power by virtue of its relative price stability compared to fossil fuels, reduces portfolio generation costs. Wind and other zero fuel cost technologies therefore have a positive effect on the overall energy mix. **Several studies have shown that when added to a risky, fossil-dominated generating portfolio, wind and other fixed-cost, zero fuel cost renewables reduce overall generating cost and risk.**

Balancing costs, grid extensions cost and grid reinforcement cost come along with all electricity generating technologies, not only with wind power. Still, it is impossible to find any study on the system cost (balancing requirements, grid extensions and reinforcements) of other technologies than wind power, hence proper cost comparisons are not possible. **As a minimum requirement, grid operators, conventional power producers and international institutions should study the additional system costs for all other technologies than wind power.**

Likewise, **most countries and institutions continue to ignore the risk element of volatile fuel prices when making cost comparisons between different electricity generating technologies.** Rather than using the commonly applied levelised cost approaches, it is recommended to adopt cost calculating methods allowing a proper economic interpretation of (easily quantifiable) cost and risk of volatile oil, gas and coal prices.

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4. Recommendations

This report makes the following recommendations related to the integration of wind power into the European electricity infrastructure:

1. Improved system operation

Imbalance payments and settlement on individual turbine level should always be avoided. It is the overall variability of output from all wind farms that is relevant to system operation. The institutional and market set-up should take into account that balancing costs should reflect the aggregate imbalance rather than the individual wind farm or wind turbine output variation, as is often the case.

Long gate-closure times should be reduced for variable output technologies. There is no technical justification for having wind power predict future production 48 hours in advance as demanded by some grid operators. The shorter the gate-closure time for wind power is, the lower the overall cost to consumers.

More effective balancing and settlement procedures that do not discriminate against variable output technologies must be introduced.

Distribution grids must be more actively managed.

Curtailment of electricity production should be managed according to least-cost principles from a complete-system point of view. As wind power is free, constraining of wind power should be the last solution and restricted to a minimum.

The balance market rules must be adjusted to improve accuracy of forecasts and enable temporal and spatial aggregation of wind power output forecasts.

Imbalances payments should be settled according to monthly net imbalances as established in e.g. California and Spain.

2. Fair and adequate grid connection requirements

Often grid codes contain very costly and challenging requirements that have no technical justification. They are often developed by vertically-integrated power companies, i.e. within companies in competition with wind farm operators, in highly non-transparent manners. Furthermore, there are continuous changes of grid codes, technical requirements and related regulation, often introduced on very short notice and with minimum involvement of the wind power sector.

The general frameworks for integrating wind power should acknowledge that technical requirements - such as grid codes, curtailment practices, reactive power etc. - depend to a large extent on the wind power penetration levels and the nature of the existing infrastructure, e.g. interconnectors and the overall generation mix.

Grid codes and other technical requirements should reflect the true technical needs and be developed in cooperation with independent and unbiased TSOs, the wind energy sector and independent regulators.

Grid codes and grid access requirements should take into account that, at low penetration levels, excessive requirements such as fault-ride-through capability and voltage control possibilities are often imposed on wind power generators without being technically justified. Costly requirements should be included only if they are technically required for reliable and stable power system operation. The assessment of the requirements should be made by independent bodies – not by transmission operators that are affiliated with vertically-integrated power producers.

3. Grid infrastructure upgrade

A large geographical spread of wind power on a system should be encouraged through planning and payment mechanisms and the establishment of adequate interconnection. From a system and cost point of view that will reduce variability, increase predictability and decrease / remove situations of near zero or peak output.

The cost of grid extension should be socialised. One reason to do it is that grids are natural monopolies.

Grid connection charges should be fair and transparent and competition should be encouraged.

In future developments of the European power systems, increased flexibility should be encouraged as a major design principle (flexible generation, demand side management, interconnections, storage etc.). Besides, public private partnership and use of structural funds should play an important part.

The benefits of distributed generation, e.g. reduced network losses and reduced need for grid reinforcements, must be recognised.

4. Proper credit to wind contribution to system adequacy

Proper, uniform standards for the determination of wind power's capacity credit must be developed. As this report shows, for small penetrations of wind power – which is still the case in most European power systems – the capacity credit of wind power will be equal to the load factor in times of peak demand. For very high penetration levels, the capacity credit is reduced but never anywhere close to zero. European transmission system operators associations should – instead of referring to wind power as "non-usable power" recognise wind power's proper capacity credit, established on solid proof, by 20 years of experience and extensive research.

5. Solving institutional inefficiencies

Solving the historic structural inefficiencies in the European power sector will not only form the basis for real competition in the European power markets, it will also go a long way in removing grid barriers for wind power and other renewables and develop a European electricity supply system based on indigenous, clean, cheap and reliable technologies to the benefit of European consumers and the overall competitiveness of the Community.

In order to solve current inefficiencies, possible actions include:

- Reduction of market dominance and abuse of dominant positions
- Effective competition policies in the power sector
- Full legal and ownership unbundling between transmission/distribution, production and trading activities
- Improvement and expansion of cross-border interconnections between Member States
- Undistorted third-party access to the grids at fair tariffs and removal of discriminatory practices
- Adequate grid codes that reflect the nature of the technologies, developed in cooperation with industry and regulators

Electricity grids are natural monopolies and, hence, transmission and distribution must be effectively, i.e. legally and ownership-wise, separated from electricity production and electricity trading. The current structure leads to biased grid operators in many countries, which are more concerned with optimising profits for their affiliated power producers and traders, than to find the most cost-effective solutions to operate and extend the grids and provide fair third-party access to new technologies.

The existing guidelines for trans-European energy networks (TEN-E Guidelines) could provide a good framework for upgrading the European grid infrastructure, which has been characterised by underinvestment during the 1980s and 1990s. However, it requires dramatically increased efforts in terms of both funding and focus in application of the guidelines. The challenge of creating the necessary infrastructure for reaping one of Europe's largest indigenous energy sources – offshore wind power – should be coordinated at a European level. To that extent the TEN-E framework could be applied more effectively. On average the funding available under the framework has only contributed to 1.5% of total investment costs.

The nascent trans-national grids must be prepared to absorb offshore wind power and utilise continental smoothening effects. The Trans-European Networks for Energy (TEN-E) provide a vehicle to realise this concept but much more European cooperation is needed in this area.

The European Commission has suggested that a European policy for offshore wind energy may be needed. Furthermore, in October 2005 policy makers, NGOs and industry from a number of European countries signed the Copenhagen Strategy which *"calls on the Council of Ministers to ask the European Commission to initiate a policy for offshore wind power, in the form of an Action Plan for offshore wind power deployment"*. An Action Plan for offshore wind power that addresses offshore infrastructure would be a first step towards radically improving European energy independence and lead EU closer to real competition in the Internal Electricity Market. A European super-grid should be developed to bring large amounts of offshore wind power to European consumers, similar to the way European gas pipelines have been constructed.

6. New and continued research and development efforts

There is great need to increase funding to both short-term and long-term R&D in wind energy development at national and European level, in order to further develop onshore and offshore technology, enable the integration of large-scale renewable electricity into European energy systems and maintain European companies' strong global market position in wind energy technology. Cross-border collaboration, European co-ordination and greater interaction between public and private stakeholders are required to develop the necessary critical mass to meet the technological challenges. It is also vital to ensure that the funds applied are spent efficiently in order to maximise research output for a given amount of funds. This should be facilitated by the establishment of a Wind Energy Technology Platform under the 7th EU Framework Programme for research.

Specifically on grid integration of wind energy, more research is needed in the following areas:

a. Improved forecast methods;
b. Methods for investigating dynamic interaction between wind farms and power system;
c. Transmission network studies on transnational level;
d. Uniform methods for national system studies for balancing (reserve capacities and balancing costs);
e. Investigation of solutions to increase power system flexibility;
f. Systematic output monitoring to validate theories on capacity credit.

7. Stakeholder involvement

Wind power is capable of supplying a share of European electricity supply comparable to the levels currently being met by conventional technologies such as fossil fuels, nuclear and large hydro power. Such penetration levels, however, would require cooperation between decision-makers and stakeholders in the electricity sector on making the necessary changes to the European grid infrastructure that has been developed with traditional centralised power in mind.

Stakeholders in this process should include:

- **Wind industry:** 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;
- **Public authorities:** energy agencies, ministries, national and regional authorities, regulators, European institutions;
- **Users:** industrial and private electricity consumers, energy service providers, consultants and R&D institutes.

The table below outlines some of the issues and challenges that need to be addressed in order to remove barriers and develop strategies for well-planned and improved large-scale integration of wind power in the power system.

Issues		Stakeholders			
		Wind industry	Power sector	Public authorities	Users
Grid connection requirements	Insufficient understanding of wind farm and grid interaction at distribution system operator level, leading to long delays in connection approvals for developers and wind turbine manufacturers	✓	✓		
	All aspects of dynamic interaction of system and wind power plants not yet fully understood	✓	✓		
	Large variety of grid code requirements, often with no technical justification, throughout Europe creating complex situation for wind turbine manufacturers	✓	✓	✓	
	Implementation of unduly heavy grid code requirements in countries with low wind power penetration	✓	✓	✓	
Contribution to system adequacy	The valuation of the capacity credit of wind power in a correct way in system planning	✓	✓	✓	
	Collection of operational data for determining wind power capacity credit for strategic system planning	✓	✓		
Grid infrastructure	Optimisation of existing grid infrastructure transmission system, taking into account voltage variations and power flows induced by wind farms (FACTS) and the utilisation of the lines by wind power		✓		
	Socialisation of grid extension cost (Grids are natural monopolies)			✓	
	Transparent and fair grid connection charges		✓	✓	
	Planning of system-wide infrastructure improvements in view of long authorisation times required		✓	✓	
	Strategy for a European super-grid for collecting offshore wind power (TEN-E Framework)	✓	✓	✓	
	Construction and allocation of transmission and interconnection capacity	✓	✓	✓	
Operation of the system	Further development of methodologies used in system studies	✓	✓		
	Introduction short gate-closure times			✓	
	Efficient use of forecast in connection with balancing (high-quality forecast tools, and smart implementation, i.e. not day-ahead, but as close to delivery as possible)	✓	✓		
	Making the power system more flexible (storage, demand side, interconnection) to avoid curtailment and thus wasting of wind power generation		✓	✓	✓
	More active management of distribution grids in view of improved accommodation of embedded generation		✓	✓	
Institutional and legal issues	Full legal and ownership unbundling		✓	✓	
	EU policy on offshore wind energy (Action Plan)			✓	
	Implementation of fair payment rules and gate closure times	✓	✓	✓	
	Facilitation of grid investments through the TEN-E Framework			✓	
R&D, demand side management and storage	Further research and development in the area of storage technologies	✓	✓	✓	✓
	Implementation of demand side management (in technology, incentives etc.)		✓	✓	✓

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Symbols and abbreviations

AC	Alternating Current
CCASG	Converter Connected Asynchronous Generator
CHP	Combined Heat and Power
COD	Concerted Action Offshore Wind Energy Development
DFIG	Doubly Fed Induction Generator
DSM	Demand Side Management
DSO	Distribution System Operator
EEZ	Exclusive Economic Zone (offshore)
FACT	Flexible AC Transmission System Device
FRT	Fault Ride Through
GDP	Gross Domestic Product
GW	Gigawatt
GWh	Gigawatt hour
HVAC	High voltage AC
HVDC	High voltage DC
IGBT	Insulated Gate Bipolar Transistor
ISET	Institut fur Solare Energietechnik (Kassel, Germany)
ISO	Independent System Operator
LCC	Line Commutated Converter
MVAR	Mega Volt Ampere Reactive
MW	Megawatt
MWh	Megawatt hour
NETA	New Electricity Trading Arrangements
NGC	National Grid Company
NREL	National Renewable Energy Laboratory (Boulder, USA)
NRMSE	Normalised Root Mean Square Error
NTC	Net Transfer Capacity
NWP	Numerical Weather Prediction
OTC	Over-The-Counter Markets
PIRP	Participating in Intermittent Resource Programme
PMSG	Permanent Magnet Synchronous Generator
RMSE	Root Mean Square Error
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
UCTE	Union for the Coordination of Transmission of Electricity
VPP	Virtual Power Plant
VSC	Voltage Source Converter
WEPP	Wind Energy Power Plant
WRIG	Wound Rotor Induction Generator

1 Turning the energy challenge into a competitive advantage

Energy - rising costs and uncertainty

Abundant and relatively cheap sources of energy are a pre-condition for the levels of economic and social progress enjoyed across the developed world for the past two centuries. Secure energy supplies are vital for the well-functioning and competitiveness of the European economy. However, most observers agree that the era of cheap and unlimited supplies of energy is over.

Rising oil prices

The price of oil and gas had remained fairly static for nearly two decades and this had lulled many into a false sense of security. The price of oil has more than tripled since 2001. Less than a year ago crude oil prices were in the range of $25 to $35 a barrel, but in August 2005 reached an all-time high of more than $70. The last three global recessions were caused by oil price rises. The IMF says that "*oil prices will continue to present a serious risk to the global economy*", whilst according to the International Energy Agency, world economic growth could be reduced by 0.8% this year as a result of record oil prices. It is clear that world oil and gas prices have risen much more quickly than anticipated by commentators and it is also evident that the EU dependency on imported fossil fuel energy has become a threat to economic stability because of the impact of increased fuel prices on the cost base, especially on the price of electricity, as the price of gas has followed the same trend. Forecasts of economic growth are being revised downwards as the impact of higher fuel prices sinks home.

The global economy underwent a paradigm shift in the 1990s with the emergence of China and India as major players in international markets, including the market for internationally-traded energy products. Demand for oil and gas took off exponentially and intensified to the extent that it spilled over into competition for the ownership of oil and gas fields around the world. At the same time, fears emerged about the real level of known and realisable oil and gas reserves, or when the production peak for oil will occur. This coincided with fears over the security of supply coming from politically unstable regions and justified alarm at the adequacy of refining capacity to satisfy demand, particularly in the medium to long term.

Environmental constraints

The arrival of the era of energy uncertainty, moreover, coincides with the emergence of concern for the environment, most specifically climate change. The issue here, as is widely acknowledged, is that the use of fossil fuels at the levels prevalent over the past half century, and forecast to continue in the absence of action to dampen demand, cannot be tolerated if the global ecosystem is to be protected from irretrievable damage. Limiting carbon from fossil fuels is at heart of climate change policies.

In short, the mood has changed within a decade from one of relative security about the supply and price of energy to a sense of growing insecurity about the price and availability of fossil fuels. This has led some policymakers to remark that the world has moved from an era of energy security to one of energy insecurity.

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New policy paradigm

The imperative of environmental protection has complicated the policy challenges beyond anything anticipated even as recently as a decade ago. We are now confronted with a new policy paradigm and must search for solutions to problems never previously encountered. In these circumstances, it is prudent for the European Union to re-assess the fundamentals on which its energy and environmental policies are based.

It is clear that the decades ahead will be characterised by intensified competition for fossil fuels which will inevitably push up prices, lead to periodic scarcity and precipitate a scramble for reserves among the world's main economic blocks. The continued economic and social progress of regions like Europe will depend in the medium term on their ability to compete robustly for existing fossil fuels and, in the longer run, on their ingenuity in developing new energy sources which are independent of international competition and benign for the environment. That this is a tall order goes without saying but it is the key policy challenge for the century ahead.

Competitive advantage

The challenge of securing energy at affordable prices must first be assessed in the context of Europe's competitive and comparative advantage, within the framework of the geopolitics of the global energy market. Exposure to fossil fuel volatility is common to all economies, but is particularly acute for Europe because of its inordinately high dependency on internationally traded fossil fuel products.

For energy purposes the world can be thought of as consisting of major economic blocks, each facing the same energy future and each competing against the other over the next decades for dwindling non-renewable resources. It is sometimes argued that this dependency constitutes neither an economic nor a political problem since oil and gas can be successfully imported in sufficient quantities, even at the very high price levels of 2005, and that Europe could plan to do so indefinitely into the future. But this approach ignores the fundamentals of competitive bargaining in a world of diminishing resources, a world for which Europe is singularly ill-equipped in comparison to the blocks against which it will compete.

The economic context to competitive bargaining is that China is growing at a rate of 9% per annum, India at 8.3% per annum and the United States between 4 – 5% per annum. By contrast, the European economy is suffering from an annual growth rate of only 1%, with little prospect that it will improve in the medium term. This constitutes an imbalance between the bargaining strengths of the big economic blocks to the disadvantage of Europe.

With regard to population there is a more profound imbalance between Europe and the other agglomerations. The population of China is at least 1.3 billion, with India around 1.1 billion and the two together account for about 40% of the world's population. Although the United States has a relatively small population of 298 million it is the world's economic super power. The EU population is around 450 million and is likely to decline if current demographic trends continue. Thus, when it comes to bargaining power based on economic strength and population, Europe presently lags behind China and the United States and will fall behind India should the differential in growth rates be sustained. At that stage Europe will be at the end of the queue in terms of competitive advantage. Europe is poorly positioned strategically in global competition for fossil fuels, and is particularly vulnerable to price volatility and disruption of supply.

European energy realities

Europe is a major consumer of hydrocarbons. It is the world's largest importer of oil and natural gas[2]. Most of the oil comes from the Middle East and virtually all of the gas comes from just three countries: Russia, Algeria and Norway. Energy consumption in Europe is rising at around 1-2% per annum[3]. Europe stands out in a global context as an energy-intensive region, heavily reliant on imports.

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2 & 3 Energy: Let us overcome our dependence. DG TREN 2002.

In its Green Paper on Security of Energy Supply from 2000[4] the European Commission concluded that, unless there was a change of direction, by 2030 Europe would be importing 70% of its energy as compared to 50% at present. The Commission's baseline scenario highlights that by 2030, oil imports would rise from 76% to 88% and gas imports from 50% to 81%, compared to 2000. 80% of incremental energy consumption is expected to come from gas[5].

The report warned that the EU had a "*structural weakness regarding energy supply*" and stated that the EU "*must take better charge of its energy destiny*." Because of the global fossil fuel dynamics, the interconnected nature of individual Member States decisions, particularly on climate change and internal markets, "*Energy policy has assumed a new Community dimension.*"

■ Current policy framework

Following the adoption of the 1997 Treaty of Amsterdam, the European Union now bases its energy policy on three core principles, namely:

- Environmental protection – in both energy production and energy use to maintain ecological and geophysical balances in nature;
- Security of supply – which aims to minimise risks and impacts of possible supply disruption;
- Competitive energy systems to ensure low cost energy for producers and consumers.

Community policy initiatives on energy since 2000 have focused primarily on three areas: supply security, market opening and environmental concerns[6]. In 2003 the European Commission published a scenario report which examined energy futures to 2030. The Commission's report was updated in 2004[7], with a range of scenarios and stated that: "*The EU25 Energy system will need to deal with a number of major challenges over the next 30 years, including issues related to security of supply, tightening environmental pressures, competitive energy prices and critical investment decisions*".

■ New power and infrastructure demand

According to the European Commission's Baseline (business as usual) scenario, electricity production increases by 52% between 2000 and 2030. Total installed power generation capacity will increase by about 400 GW, from 656 GW in 2000 to 1118 GW in 2030, a figure that includes a significant amount of current power stations to be retired or decommissioned. The total new build requirement in Europe by 2030 is estimated to be 761 GW, of which 365 GW will be needed to replace retired capacity. The Baseline scenario acts as a reference case against which other options are compared. A dramatic increase in power consumption will require substantial investments in generation assets. According to the IEA, the EU needs to invest €100 billion in transmission networks and €340 billion in distribution networks for reinforcement, asset replacements and new connections over the three decades from 2001 to 2030.

■ Fossil fuel volatility

The relationship between fuel and electricity price increases is complicated by the fact that investment in power generation using internationally-traded fuel sources demonstrably fails to deliver long-term price stability. Despite this danger the development of the electricity system over the past quarter century has largely been led by investments in generation plant fired by gas. The level of fuel risk in electricity systems has correspondingly increased. In an era of low international fossil fuel prices, this strategy delivered cheap electricity but in an era of high international fuel prices it can only deliver expensive electricity. This is particularly so given that the fuel component of the generation cost is 60% or more in modern gas turbines.

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[4] Towards a European strategy for the security of energy supply. Green Paper DG TREN 2000
[5] European Energy and Transport - Scenarios on key drivers. DG TREN September 2004
[6] 2003 - Annual energy and transport review. DG TREN December 2004
[7] European Energy and Transport - Scenarios on key drivers. DG TREN September 2004

■ Free fuel

Wind power has unique characteristics: it has zero fuel price risk, zero fuel costs and extremely low operation and maintenance costs. In addition, wind provides total protection and zero risk from carbon costs, and zero geo-political risk associated with supply and infrastructure constraints or political dependence on other countries. Wind power has no resource constraints; the fuel is free and endless. Unlike conventional fuels, wind is a massive indigenous power source permanently available. Wind power stations can be constructed and deliver power far quicker than conventional sources. In a world of expensive fuels, the merits of a technology providing a free-fuel supply are indisputable.

■ Secure indigenous resources

Back in 2000, when fuel prices were a fraction of today, the European Commission's Green Paper on Security of Supply recognised the potential of renewable energy sources:

"Renewable sources of energy have a considerable potential for increasing security of supply in Europe. Developing their use, however, will depend on extremely substantial political and economic efforts. […] In the medium term, renewables are the only source of energy in which the European Union has a certain amount of room for manoeuvre aimed at increasing supply in the current circumstances. We can not afford to neglect this form of energy."

It continued:

"Effectively, the only way of influencing [European energy] supply is to make serious efforts with renewable sources."

In 2003 , the European Commission estimated that wind energy would be the main contributor to meeting the 2010 targets for renewable electricity in the European Union.

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It is essential that Europe develops technologies that enable it to exploit its own internal energy resources to the maximum extent possible, as well as promoting energy efficiency. Fortunately, Europe has at least one such source of energy and, it is one in which it already has both a competitive and a comparative advantage. There is sufficient wind energy on and offshore to meet Europe's power needs into the future. Unless Europe taps into this indigenous energy resource the Union will be further exposed to economic distress resulting from dependence on foreign energy supplies at unpredictable costs. Without reliable, sustainable, and reasonably-priced energy there can be no sustainable long-term growth and Europe will become economically disadvantaged.

The key point to be emphasised about developing onshore and offshore wind power in Europe is that this form of energy will never be internationally traded and hence will protect the European economy from escalating energy costs and periodic fuel shortages. Once developed at large scale, wind power will provide Europe with electricity generated from a free-fuel source and electricity at predictable and falling cost. The fact that the power source is free and clean is, of course, economically and environmentally significant but the more fundamental point at issue is that the cost of the power source is fixed and predictable. The long-term implication is that the economic future of Europe can be planned on the basis of certain energy costs derived from an indigenous energy source free of all the security, political, economic and environmental disadvantages associated with oil and gas.

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Competitively, the exploitation of its own wind reserves and resources would mean that Europe would be independent of demand patterns in China, India and the United States and, simultaneously, be able to reap industrial benefits from exploiting its knowledge edge in wind turbine technology. The fact that the power source is environmentally friendly is important in its own right but is not germane strategically. The fact that the power source is sustainable indefinitely is the key issue.

Europe's energy challenge

For Europe as a whole one of the main challenges ahead is that there is no regulatory or physical grid structure in place to allow the full exploitation of its vast wind reserves. They will have to be built at a significant cost, yet irrespective of whatever policy is chosen by the EU, massive investment in generation plant and grids is already required. For policy-makers, the question is the priority to be assigned to different technologies and fuels. In this context it should be remembered that there were no gas grids in the North Sea in 1960 and that this did not prove a deterrent to the development of a European gas industry.

Progress of wind energy

Wind energy constitutes a mainstream power technology that is largely underexploited. Wind technology has made major progression from the prototypes of just 25 years ago. Two decades of technological progress has resulted in today's wind turbines looking and being much more like power stations, in addition to being modular and rapid to install. A single wind turbine can produce 200 times more power than its equivalent two decades ago. The wind power sector includes some of the world's largest energy companies. Effective regulatory and policy frameworks have been developed and implemented in a handful of countries, and Europe is the world leader in wind energy. Whilst the technology has been proven, we are only seeing the tip of the iceberg of the true deployment potential of wind power.

To move wind from being a small electricity player producing 2.4% of European electricity to a major supplier of 12% of European electricity production in 2020 and over 20% in 2030 will require a concerted effort at EU national, regional and local level. Significant investment in the existing transmission infrastructure will be required to facilitate continued onshore development together with investment and development of offshore sites.

Barriers to wind

Wind power is disadvantaged compared to the situation under which conventional power sources such as oil, gas, coal and nuclear power sources were developed and introduced. Until the 1980s, electricity generation, distribution, grid reinforcement, grid extensions, and electricity selling were undertaken by national, vertically-integrated monopolies that were granted exclusive rights and mandates to finance investments and research in new capacity and technologies through state subsidies and levies on electricity bills. As Europe is moving in the direction of more liberalised power markets, those options are no longer available and new technologies are facing a more challenging environment on the path to market penetration and maturity.

There are numerous distortions in the European power market in Europe, which is comprised of 95% non-renewable energy. These distortions include, for example: institutional and legal barriers, large subsidies and state aid to fossil fuel and nuclear power, exclusion of external costs from prices, existence of regional and national dominant players, potential for abuse of dominant positions, barriers to third-party access, limited interconnection between regional and national markets; discriminatory tariffs, and no effective unbundling of production and transmission. For example, public funding for energy research and development has been drastically reduced. Over the last three decades, 92% of all energy R&D funding ($267 billions) was spent on non-renewables – largely fossil fuels and nuclear technologies – compared to $23 billion for all renewable energy technologies

The European Commission – through a project called ExternE[8]– has tried to quantify the true costs, including environmental costs of electricity generation. It estimates that the cost of producing electricity from coal or oil would double and the cost of electricity; production from gas would increase by 30%, if external costs, in the form of damage to the environment and health, but excluding climate change, were taken into account. The study further estimates that these costs amount to 1-2% of EU GDP or between € 85 billion and € 170 billion per annum, not including the additional costs of the impacts of human-induced climate change on human health, agriculture and ecosystems

■ Next steps

For the next stage of progress, one of the core challenges is how to effectively integrate significant amounts of wind energy into the European electricity system, and specifically what are the technical, economic and regulatory issues. This report analyses these challenges and provides comprehensive assessment and solutions.

The report concludes that a large contribution from wind energy to power generation is technically and economically possible, in the same order of magnitude as the contributions from conventional technologies used nowadays. It details that the constraints of increasing wind power penetration are not inherent technical problems with wind technology *per se*. Rather they are a matter of cost allocation, regulatory, legal, structural inefficiencies and market changes, and are part of a broader power market situation. In this respect, this report is addressing issues that are often the source of 'myths' used against wind power. The issues are presented based on a detailed overview of best practice, description and reference to technical and economic assessments. The report collects and presents detailed facts and results published in specialised literature and contributions from experts and actors in the sector.

■ Roadmap to read the report

The impacts on and challenges for the grid are summarised in Chapter 2, and these are further developed in the subsequent chapters. The specific technical characteristics of wind power as a player in the generation portfolio are discussed in Chapter 3, notably technical characteristics of wind power plants, variability and, predictability of wind power. Operation of the power system on the generation and transmission level is discussed in Chapter 4, with special emphasis on technical and economic aspects of balancing the system, taking into account the additional variability in the system introduced by wind power. The interconnection issues, notably grid stability and grid codes are outlined in Chapter 5. The implications for grid infrastructure upgrade, onshore and offshore, are outlined in Chapter 6. How wind power can contribute to the adequacy of the power system is discussed in Chapter 7. Chapter 8 summarises the economic impacts of large scale grid integration, by discussing the overall system integration costs. Finally, Chapter 9 discusses the institutional, market and legal issues associated with large scale wind integration. In the inlay an introduction is given to the European grid systems and the present position of wind power in the power system of member states is described in country profiles.

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[8] External costs. Research results on socio-environmental damages due to electricity and transport. DG Research 2003

2 Enabling wind power as mainstream power supplier: challenges and issues

2.1 General

In view of the developments in the European energy and electricity markets and the increasing amount of decentralised generation, including the growing importance of wind power capacity in a few European regions, it is important to analyse the technical, economic and regulatory issues that relate to the expected increased penetration of wind energy on electricity systems.

One part of this debate centres on the perception that because wind energy is variable, this is a fundamental barrier to its future growth, and the operation of electricity systems. It is sometimes expressed that wind energy is inherently unreliable because it is variable.

This report includes a comprehensive review of the relevant literature, analysis, simulations and data available that allows an informed assessment of the issue. **It contains a detailed investigation of the technical, economic and regulatory issues concerning an increasing proportion of wind energy in the electricity grids, with attention paid to the aspects of variability.** This report is intended as a guide to all aspects of grid integration of wind energy and seeks to assist in the political debate, policy formulation, research and investment decisions.

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It is important to note that the end product that wind delivers is exactly the same as other power sources (gas, coal, hydro or nuclear), i.e. electricity, and that is the arena of relevance.

This chapter gives an overview of the main system impacts of wind power integration, and summarises the six main issues to be improved and resolved in the process of wind power becoming a mainstream player together with conventional technologies. The specific characteristics of wind power are described in Chapter 3 and the six main issues are further elaborated in Chapters 4 to 9.

What does variability mean? – tackling the intermittency myth

Electricity production and consumption is variable. Electricity supply and demand are inherently variable, and are influenced by a large number of planned and unplanned factors. The changing weather makes millions of people switch on and off heating and lighting. Hundreds of millions of people in Europe switch on and off equipment that demands instant power - lights, TVs, computers. A classic example is the power 'surge' that occurs during sporting cup finals and where a completely unpredictable event like extra-time has a major impact on demand and causes an immediate unbalance between forecasted and actual demand. The varying demand of industrial production, e.g. from factories and general consumer behaviour, creates variability on the demand side and has been successfully addressed since the dawn of electricity.

Power stations, equipment and transmission lines break down on an irregular basis, or are affected by extremes of weather such as drought, which particularly impacts hydro and nuclear energy. Trees fall on power lines, or are iced up and cause sudden interruptions of supply. Power demand from a neighbouring country can put a strain on supply. Changes in spot market electricity prices immediately impact decisions about which power stations to start up or shut down.

The entire electricity system is variable, both on the supply and demand side, and both can be predicted. The issue, therefore, is not one of variability or intermittency of a particular technology *per se*, but how to predict variability and what tools to utilise in order to control the process of constantly matching production to demand.

An electricity system is essentially like a big bath tub with hundreds of taps providing the input (power stations) and millions of plug holes (consumers). The taps and the plugs are opening and closing all the time. Therefore water level is always moving, and as long as the level of water is kept within a specified limit, that provides an ability to 'maintain' system security. The system operators need to balance out planned and unplanned changes in supply and demand in order to maintain systems security. This is done through reserves. Variability in electricity supply is as old as variability in demand; it has been a feature of electricity systems since its inception. At modest penetration levels, the variability of wind is always dwarfed by the normal variations. Therefore wind cannot be analysed 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 aspects determining the systems' capability of accommodating a high amount of wind power

The role of a variable power source like wind energy needs to be considered as one aspect of a variable, dynamic electricity system.

Wind energy is a technology of variable output. It is sometimes incorrectly expressed that wind energy is inherently unreliable because it is variable. Wind power is also sometimes incorrectly described as an intermittent energy source. This is misleading, because on a power system level, wind power does not start and stop at irregular intervals, which is the meaning of intermittency.

The variability of the wind energy resource needs to be examined in the wider context of the power system, rather than at the individual wind farm or wind turbine level. The wind does not blow continuously at a particular site, yet there is little overall impact if the wind stops blowing somewhere – it is always blowing somewhere else. Thus, at system level, wind can be harnessed to provide stable output even though the wind is not available 100% of the time at a particular site. In terms of overall power supply, it is largely irrelevant what happens when the wind stops blowing at the site of a single wind turbine or wind farm. Moreover, until wind becomes a significant number of the 'taps' on the bath tub, there is negligible impact on system variability.

Because the wind resource is variable, it is sometimes argued that wind energy per se is not reliable. No power station or technology is completely reliable – all system assets 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 requirement for applying reserve capacity.

By contrast, at systems level, wind energy does not suddenly trip off. Variations in wind energy is 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 the shut down of a 2 MW wind turbine. It will have to respond to the shut-down of a 500 MW coal fired plant or a 1,000 MW nuclear plant instantly.

For small penetration levels of wind power in a system, grid operation will not be affected to any significant extent. Wind power supplies less than 3% of overall EU electricity demand but there are large regional and national differences. The already established control methods and backup available for dealing with variable demand and supply are more than adequate for dealing with the additional variable supply such as wind power at penetration levels up to around. 20% of supply, depending on the nature of a specific system. For larger penetration levels, some changes may be needed in power systems and their method of operation to accommodate the further integration of wind energy.

In Denmark, the country in the world with the highest penetration of wind power, 21% of total consumption was met with wind power in 2004. In the west-Denmark transmission system, which is not connected to the eastern part of the country, some 25% of electricity demand is met by wind power in a normal wind year and, on some occasions, the wind has been able to cover 100% of instantaneous demand.

The integration of large amounts of wind power is often dismissed as impossible and many grid operators are reluctant to make changes in long-established procedures to accommodate wind power. In Denmark, the grid operator was initially sceptical about how much wind power the system could cope with. The concern of many grid operators to wind power can best be illustrated by the following quote from a speech on 23 April 2003 delivered by Mr Hans Schioett, chairman of the TSO in west-Denmark, Eltra (now part of Energinet Danmark), at the presentation of the company's annual report.

"Since the end of 1999 – so in just three years – wind power capacity in the Jutland-Fyen system has increased from 1,110 MW to 2,400 MW. In installed capacity that is twice the capacity of the «Skydstrup» power Plant near Aarhus. Seven or eight years ago, we said that the electricity system could not function if wind power increased above 500 MW. Now we are handling almost five times as much. And I would like to tell the Government and the Parliament that we are ready to handle even more, but it requires that we are allowed to use the right tools to manage the system".

In the western Energinet (formerly Eltra's) supply area, wind energy covers some 25% of electricity demand in a normal wind year and it is not a technical problem to handle more – it is a regulatory issue. The tools for managing more wind power in the system are developed and grid operators should be allowed to use them.

Ultimately, experience with wind power in the areas of Spain, Denmark, and Germany that have large amounts of wind power in the system shows that the question as to whether there is an upper limit for renewable penetration into the existing grids will be an economic and regulatory one rather than a technical issue. In those areas of Europe where wind power development is still in its initial stage, many lessons can be learned from Denmark, Germany and Spain. However, it is important that stakeholders, policy makers and regulators in those emerging markets realise that the issues that TSOs in those three countries are faced with will not become an issue until much larger amounts of wind power are connected to the national grids.

One of the biggest mistakes in parts of the public debate about integrating wind power is that it is treated in isolation. Wind power has distinct technical features just like any other electricity generation source. Nuclear power and some of the gas and coal fired power plants are very inflexible and are maintained at constant generation level. Seen in isolation, this is an undesirable feature because electricity demand varies significantly and constantly throughout the day. Other coal and gas plant, and hydro are more flexible and outputs can be changed more rapidly. Integrating wind power has other distinct features. The point is that no technology, neither "base load" nuclear power nor variable production wind power, should be dealt with in isolation. It is the combined effects of all technologies, as well as the demand patterns, that matter for grid operators.

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2.2 Summary of impacts of wind power on the power system

■ Short-term and long-term impacts

The impacts of wind power on the power system can be categorised in short-term and long-term effects (ref. 2). The short-term effects are caused 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.

■ The impacts in the system are both local and system-wide.

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

On the 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 centres and certainly at low penetration levels. On the other hand, wind power may necessitate 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 high-resource sites such as offshore to the load centres, new lines have to be constructed, just as it was necessary to build pipelines for oil and gas. In order to maximise 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 requires measures for regulating control just as any other technology (secondary and tertiary control, see Chapter 4), and – depending on penetration level and local network characteristics – impacts the efficiency of other generators in the system (and vice versa). In the absence of sufficient intelligent and well-managed power exchange between regions or countries, a combination of (non-manageable) system demands and generation may result in situations where wind power has to be constrained. Finally wind power plays a role in maintaining system stability and contributes to the system adequacy and security of supply. Table 1 gives an overview and categorisation of the effects.

Table 1: Power system impacts of wind power, causing integration costs

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

Source: ref. 2

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 this report, the term 'wind power penetration' indicates the fraction of the gross (annual) electricity consumption[9] that is covered by wind energy. Presently, the average energy penetration level of wind power in Europe is some 2.5%, and the EWEA target is to reach 12% by 2020. As explained in Chapter 8, wind energy penetration at low to moderate level is a matter of costs, as demonstrated by various national and regional integration studies. The integration costs related to the impacts listed above are quite modest (see Chapters 4, 6 and 8).

The assessment of how the integration costs beyond this 'low to moderate' level will increase, depends on how one looks to the future evolution of the power system. Some integration studies which implicitly assume that the system remains static as wind power is added, find sharply increasing integration costs beyond a certain penetration level.

Yet the 'static power system' assumption becomes less plausible with increasing wind penetration, because wind serving a substantial (higher than 25%) fraction of the demand will take time to develop. Furthermore, the generation mix is likely to change significantly during this long period of wind development (DeCarolis, ref. 60). For example, it is predicted that power generation with gas will increase dramatically (depending on fuel costs), which will make the power system more flexible. Hence, the integration costs of wind energy increase smoothly and monotonically as the penetration level increases. Costs beyond penetration levels of about 25% will depend on how the underlying system architecture changes over time as the amount of installed wind gradually increases, together with other generating technologies to meet the rapidly increasing demand. For example, in order to accommodate high amounts of wind power, a system with generation mix dominated by fast ramping gas turbines or hydro is much more flexible than a system dominated by nuclear or coal, because it can respond quickly to changes in supply and demand.

Up to a penetration level of 25%, the integration costs have been analysed in detail and show consistently low costs. The economic impacts and integration issues are very much dependent on the power system in question. 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 organisational aspects of the power system. Technically, methods used by power engineers for decades can be applied for integrating wind power. But for real large-scale integration (penetrations typically higher than 25%), new power system concepts may be necessary, and it would be sensible to start considering such concepts now. Practical experience with large-scale integration in a few regions bears witness to the fact that this is not merely a theoretical discussion. The feasibility of large-scale penetration is proven already today in areas where wind power already today meets 20, 30 and even 40 percent of consumption (Denmark and regions of Germany and Spain).

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[9] There are many ways to define 'penetration level'. For example, wind power penetration can also be indicated as the total wind power generating capacity (MW) related to the peak load in the system area. If this meaning is used, it will be explicitly mentioned, and referred to as 'capacity penetration'. 'Energy penetration' is preferred in this report, because the majority of studies reviewed measure wind power's penetration in terms of coverage of annual electricity consumption.

2.3 Main issues when integrating large amounts of wind power in the electrical system

The present levels of wind power connected to electricity systems show that it is feasible to integrate wind power to a significant extent. The experience with more than 40 GW wind power installed in Europe shows where areas of high, medium and low penetration levels in different conditions take place and which bottlenecks and challenges occur. Large-scale integration of both onshore and offshore wind raises challenges for the various stakeholders involved, 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 operation (reserve capacities and balance management, short-term forecasting of wind power, cross border flow management)
- Grid connection of wind power and system transient stability (grid codes and power quality, wind turbine technology and control issues)
- Grid infrastructure issues (congestion management, extensions and reinforcements, specific issues of offshore, interconnection)
- Contribution of wind power to system adequacy (on generation, energy source and transmission levels)
- Market redesign issues to facilitate wind power integration (demand side management, storage, balance settlement rules, time between schedule and delivery at the balance market)
- Institutional issues (vertical integration, legal and ownership unbundling, incentives of stakeholders, non-discriminatory third-party grid access, socialisation of costs, change in approach and attitude)

The above-listed areas will be briefly addressed in the remainder of this chapter and the most important issues will be identified. These will be further discussed in the following chapters.

System operation: power and energy balancing

Wind power output at first seems to present quite a challenge for the power system, often resulting in high estimates of ancillary service costs or assumptions that wind capacity must be "backed up" with large amounts of conventional generation technology, However, such assessments often overlook key factors such as (ref. 59):

- The stochastic nature of grid systems designed to routinely cope with varying and uncertain demand, and unexpected transmission and generation outages
- Actual wind power output characteristics are aggregated at the system level which results in significant smoothing effects which increase with large-scale geographic distribution of wind farms
- The ability to forecast wind power output in both hourly and day-ahead time frames
- The evolution of competitive power markets, including near-real-time operations and unscheduled deviation practices.

■ Generation level

In the absence of a perfect wind power forecast, system balancing requirements and costs are increased by random fluctuations and by forecast errors, both of variable-output wind power and of load (demand), since these are generally not correlated. It can be demonstrated that power balancing requirements due to wind power mainly address reserve power in secondary/tertiary control time scales. This reserve power is in general offered on the balancing market. The increased need for additional reserve with growing wind penetration is very modest and, up to significant wind power penetrations, unpredicted imbalances can be countered with reserves existing in the system. The corresponding additional costs are depending on many local system specific parameters. Several country- and region specific system studies indicate additional balancing costs in the order of €0 to €3/MWh wind, for levels of wind power penetration (energy basis) of up to 10%. Accurate wind power forecasting is critical to economic operation of wind power in the system, as confirmed by the experience in Denmark and Spain. There is a large variety in approaches and assumptions, for example with respect to the use of forecasting, in these system studies, and a more systematic and uniform approach is needed to make the results more comparable.

There may be occasions where wind power exceeds the amount that can be safely absorbed while still maintaining adequate reserves and dynamic control in the system. In such situations - occurring occasionally only at penetration levels of 10% of gross demand and up - a part of wind energy production may have to be curtailed. It may however prove more economic to increase demand under ‘demand side management’, e.g. by additional pumping at pumped storage facilities, heat pumps and/or water supply reservoirs. Also increased interconnection and improved power exchange rules between the countries are needed to avoid wasting wind power output in such situations.

Apart from balancing requirements from the energy perspective, the power system requires so-called ancillary services supplied by generators, ranging from operating reserve and reactive power through short-circuit current contribution and black start capability. Modern wind farms can provide part of these services. However, if reserve is provided with wind power, this is at the cost of losing production so it will not be the first and frequent option for the power system to make use of. In addition, appropriate equipment should be maintained in the system to provide the ancillary services, that cannot be delivered by wind power plants.

■ Transmission and distribution level

Wind power production has implications for the planning and operation of the transmission system. An issue is the management of power flows and possible congestions in the grid. Specific combinations – both in terms of level and in terms of geographical location – of wind power production and demand cause changes in the magnitude and direction of power flows in the transmission grid resulting in changed cross-border flows. Also for this purpose, TSOs need to apply high quality wind forecast tools. FACTS-devices, such as phase-shifting transformers, may also be used for the management of power flows.

Until recently, most new wind turbines were connected at the distribution level. A particular feature of distribution grids is that there is little active management such as at the transmission level. Nevertheless, distribution grids have to cope with varying distributed generation levels, without reducing the quality of supply. However, ‘embedded generation’ of wind power adds advantages to the grid. Weak grids may be supported by wind power, and the users on the line may be better served, as wind power adds to the grid voltage and power electronics of wind farms can improve power quality characteristics in the grid. The power – if consumed within the distribution network – gets directly to the user and transmission costs can be avoided. Finally, wind power may keep parts of the system operational in the event of transmission failures which otherwise would cause black-outs. Besides, addition of wind power introduces similar effects as in the transmission grid: changing of direction and quantity of real (active) and reactive power flows, which may affect operation of grid control and protection equipment. The design and operation practices at the distribution level may no longer be suitable for increased distributed generation and distribution grids may have to become more “actively managed”. This necessitates investments, and requires the development of suitable equipment and design principles, but the improved grid yields will benefit the distribution grid operator and, in the end, the customer.

The above issues are further discussed in Chapter 4.

Grid connection rules and system stability

Connecting wind farms to the transmission and distribution grids causes changes in the local grid voltage levels (Kling, ref.1). Careful voltage management is essential for the proper operation of the network. The actual voltage control is a highly localised activity, in order to enable the proper power flows from producer to demand. The interaction between the electricity grid and wind power plants and their effect on the dynamic stability of the grid needs to be profoundly understood. This facilitates reliable operation of the power system by the TSOs and is important for further technical development of wind power plants.

Several assessment methods exist to study the dynamic interaction of wind power plants and grids. This topic is still being researched, and further work is needed, because the models used are quite complex and are still lacking verification with field experience. It is an area where increased sharing of experience between system operators and the wind energy sector is needed.

TSOs impose grid connection requirements (interconnection regulations, grid codes) onto wind power plants – just like onto any other generator – in order to keep good order in the system and to prevent negative impacts on the network. In countries facing significant wind power development the specific rules for wind power are being further refined. In principle this allows a larger penetration and at the same time maintenance of an adequate power supply. These grid codes are country and system specific, resulting in a wide variety of requirements Europe-wide. On the other hand, Europe wide harmonisation of interconnection regulations designed for high penetration situations is not yet desirable, because in most regions of Europe, these have no technical justification given the low levels of wind power in most regions. Hence, stringent requirements would pose an unduly heavy impact on wind turbine design, cost and consumer prices. Therefore, any harmonisation should take into account that at low penetration levels, heavy technical requirements such as fault-ride-through capability and voltage control possibilities are not needed. Costly requirements should be included only if they are technically required for reliable and stable power system operation.

Most of the MW-size wind power technology installed today is capable of meeting the most severe grid code requirements, but that does not mean strict requirements should be applied for all regions. Advanced features include fault-ride-through capabilities of wind farms, enabling them to assist in keeping the power system stable when large faults occur in the system, with active voltage and power control. However, the majority of existing wind farms has been built up in a period of approximately 20 years (with a technical lifetime of 20 to 25 years). In this period a considerable technical development has taken place. As a result there are different types of technology in operation, with a range of degrees of controllability from a grid operation perspective. On one end of the spectrum, the older wind turbine types (representing approximately 40% of today's wind power capacity) are less controllable: they do not possess advanced reactive power control properties, nor fault-ride through capability, for the simple reason that grid operators required that they disconnected from the system when the system failed. Only recently, have some TSOs changed their operating procedures and now ask wind turbines to stay connected. The other end of the spectrum includes the most modern wind farms, equipped with central control systems enabling them to be operated much as power plants and to participate in network control (active power and voltage control).

The above issues are further discussed in Chapter 5.

Grid infrastructure extension and reinforcement

In general, all grid reinforcements will benefit the whole power system, not just wind power. A better interconnected European grid will also improve the functioning of the emerging internal electricity market. Transmission and distribution grids were designed and built long time before wind power came into the picture.

Today, even with the fast-growing expansion of wind power, planning of grid infrastructure and planning of wind power projects are two independent processes, certainly at the European level. The capability of the present grid infrastructure to handle wind power depends on how close the system is to its limits. Grids that optimally accommodate wind power have to take into account aspects such as:

- Remoteness of the wind resource from the demand centres;
- Changed power flows and congestions in the grid as a result of specific combinations of demand level and wind power output (for example strong wind and low load);
- Specific geographic concentrations of wind power generation because of wind rich areas (onshore as well as offshore).

In view of the above, **there is no doubt that transmission and distribution infrastructure will need to be extended and reinforced in most of the EU countries when large amounts of wind power are connected.** However, extensions and reinforcements are needed, not only to accommodate wind power, but also to connect other power sources necessary to meet the rapidly growing European electricity demand. **The present grid system, however, is not yet used to its full extent and in an optimal way. One example is that the national borders play a role in the organisation of wind power's transmission through Europe, and cause problems, whereas in reality there are no country borders for wind.** Also, present optimisation and utilisation standards and practices of transmission lines by TSOs are still largely based on the situation before wind power came into the picture. As wind power is producing in a whole range of partial load states, wind farms will only utilise the full rated power transmission capacity for a fraction of the time. In some cases where there is adjustable power production (like hydro power with reservoir), the combination wind/hydro can use the same transmission line (ref. 71).

Moreover, the need for extension and reinforcement of the existing grid infrastructure has many pressing reasons. Changes in generation and in load at one point in the network, in principle, can cause changes throughout the system, which may cause power congestion (bottlenecks). It is not possible to identify one (new) point of generation as the single cause of such difficulties, other than it being 'the straw that broke the camel's back'. Therefore, the allocation of changes of load flows in a system to a single new generator connected to the system (e.g. a new wind farm) is ambiguous, since established generators or changes in demand may cause an equal burden on the grid infrastructure.

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

The above issues are further discussed in Chapter 6.

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Power system adequacy

Power systems have to be designed to have sufficient generating capacity to meet the variable demand of the end users. Wind power influences the systems' capability of matching the evolution in the demand – in other words the system adequacy – at different levels: at generation level and at the level of transportation of the power to the consumers. The system operators make adequacy forecasts in order to support the strategic planning of generation, transmission and interconnection (ref. 145). Based on the results of these adequacy forecasts, the TSOs – especially in non fully liberalised markets – either contract (on the long-term) some capacity for (slow) reserves or rely on the power producers to act taking enough capacity on-line when necessary. In such forecasts, the contribution of wind power should be properly taken into account.

As a consequence of the conservative approaches of system operators and lack of insight on the issue of the capacity credit of wind power, the contribution of wind power to the system adequacy is often underestimated in system planning. The insights need to be more thoroughly checked based on practical experience. In order to assist the strategic planning of power systems, a continuous effort is needed in improving the insight in the actual contribution of wind power to the system security, e.g. by systematic output monitoring. It is simply unacceptable when some transmission system operators refer to wind power as "non-usable power", i.e. that wind power has zero capacity credit, despite the fact that solid proof, 20 years of experience, simple logic and numerous research have established, years back, that wind power has a positive capacity credit.

The above issues are further discussed in Chapter 7.

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Market redesign, demand side management and storage

In view of the issues discussed above, **many European electricity markets still have structural deficiencies and inefficiencies in their balancing and settlement procedures that discriminate against variable-output wind power** (ref. 77). Therefore, a re-design of corresponding market structures and procedures is seen as a precondition for integrating significant amounts of wind power into the national and international networks.

Addressing technological development in the short to medium term, implementation of improved forecasting tools will mitigate the effect of the intrinsic variability of wind generation and reduce the corresponding costs for balancing the system. From the power system point of view, the aggregated wind power forecast errors, affecting the total net imbalance, are the cause of imbalance costs. The payment rules in balance settlement should reflect the actual costs of aggregated output, instead of penalising each individual wind power producer for forecast errors. The time between bids and delivery (forecast horizon) is crucial for wind power producers, as the forecast errors increase when forecasting long ahead. Furthermore, a shorter forecast horizon has no technical impact on the operation of the grid, but may require changed procedures in the operating room.

The future role of advanced storage technologies, such as battery and fuel cell systems, in providing corresponding balancing services is not yet clear. Therefore, their market entry cannot yet be predicted or quantified, and they do not provide a solution in the short term. Electrical storage is still expensive compared to thermal storage. However, already today, less exotic storage tools are available. A power system with combined heat and power plants (CHP) has an option to use thermal storages to provide flexibility in electricity production side. This is an option used for example in Denmark to manage the few critical overproduction hours due to high winds, low demand, and cold weather: CHP plants are stopped and use thermal storage for heat, or even use wind power produced electricity to produce heat during the few critical hours of overproduction and potential congestion.

Long-term and fundamental market re-design should focus on having manageable loads on the demand-side. Such loads should change sympathetically with changes in generation, especially of intermittent and variable output generation. Such management will reduce the burden on conventional generation units for system balancing and allow a better operation of markets: both production and consumption react to market signals, hence enabling lower cost. Preconditions for significant implementation of demand response applications are (i) implementation of known and future technologies for communication between supply and demand, (ii) tariffs that encourage rapid and sufficient demand-side load changes in response to electricity price changes, i.e. have minimal transaction cost for consumers. Using electricity to provide fuel for vehicles is one technological trend that will bring new possibilities in power system management in the longer term.

The above issues are further discussed in Chapters 4 and 9.

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2.4 Summary: concerns and roles of stakeholders

Wind power is capable of supplying a share of European electricity supply comparable to the levels currently being met by individual 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 on making the necessary changes to the European grid infrastructure that has been developed with traditional centralised power in mind.

Stakeholders in this process should include:

- **Wind industry:** 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
- **Public authorities:** energy agencies, ministries, national and regional authorities, regulators, European institutions
- **Users:** industrial and private electricity consumers, energy service providers, consultants and R&D institutes.

Table 2 outlines some of the issues and challenges that need to be addressed in order to remove barriers and develop strategies for well-planned and improved large-scale integration of wind power in the power system.

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Table 2: Summary of issues and stakeholders

Issues		Stakeholders			
		Wind industry	Power sector	Public authorities	Users
Grid connection requirements	Insufficient understanding of wind farm and grid interaction at distribution system operator level, leading to long delays in connection approvals for developers and wind turbine manufacturers	✓	✓		
	All aspects of dynamic interaction of system and wind power plants not yet fully understood	✓	✓		
	Large variety of grid code requirements, often with no technical justification, throughout Europe creating complex situation for wind turbine manufacturers	✓	✓	✓	
	Implementation of unduly heavy grid code requirements in countries with low wind power penetration	✓	✓	✓	
Contribution to system adequacy	The valuation of the capacity credit of wind power in a correct way in system planning	✓	✓	✓	
	Collection of operational data for determining wind power capacity credit for strategic system planning	✓	✓		
Grid infrastructure	Optimisation of existing grid infrastructure transmission system, taking into account voltage variations and power flows induced by wind farms (FACTS) and the utilisation of the lines by wind power		✓		
	Socialisation of grid extension cost (Grids are natural monopolies)			✓	
	Transparent and fair grid connection charges		✓	✓	
	Planning of system-wide infrastructure improvements in view of long authorisation times required		✓	✓	
	Strategy for a European super-grid for collecting offshore wind power (TEN-E Framework)	✓	✓	✓	
	Construction and allocation of transmission and interconnection capacity	✓	✓	✓	
Operation of the system	Further development of methodologies used in system studies	✓	✓		
	Introduction short gate-closure times			✓	
	Efficient use of forecast in connection with balancing (high-quality forecast tools, and smart implementation, i.e. not day-ahead, but as close to delivery as possible)	✓	✓		
	Making the power system more flexible (storage, demand side, interconnection) to avoid curtailment and thus wasting of wind power generation		✓	✓	✓
	More active management of distribution grids in view of improved accommodation of embedded generation		✓	✓	
Institutional and legal issues	Full legal and ownership unbundling		✓	✓	
	EU policy on offshore wind energy (Action Plan)			✓	
	Implementation of fair payment rules and gate closure times	✓	✓	✓	
	Facilitation of grid investments through the TEN-E Framework			✓	
R&D, demand side management and storage	Further research and development in the area of storage technologies	✓	✓	✓	✓
	Implementation of demand side management (in technology, incentives etc.)		✓	✓	✓

3 Understanding the variable-output and predictability characteristics of wind power

3.1 General

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 generation. Understanding these distinctive characteristics and their interaction with the other parts of the power system is the basis for the integration of wind power in the grid.

Typical technical features of wind power plants and performance indicators which make them different from conventional power generators are discussed in paragraph 3.2. The variable-output characteristics of aggregated wind power plants and the possibilities to predict these variations are described in paragraph 3.3.

The integration of the variable-output wind power in the system – maintaining balance and reliable supply and making use of the existing capacities in the system – is not a subject of this chapter, but will be discussed in Chapter 4 in more detail.

3.2 Wind power plant characteristics and performance indicators

3.2.1 Wind power plant characteristics

In this section, essential technical characteristics of wind power plants are described to facilitate the understanding of their interaction with the electrical grid. This discussion is further divided into the wind turbine concept itself and the concepts used for wind power plants[10].

a. Wind turbine concepts

Grid connected wind turbines have been gradually evolving in the last 25 years from simple constant speed turbines to fully variable speed systems, enabling active output control. In the first category the rotational speed of the wind turbine is dictated by the electrical grid frequency and the turbine is operating below its peak efficiency at most wind speeds: at the lower end of its wind speed operational window it rotates too fast, and at the higher end it rotates too slowly. But it has proven to be a cost-effective and robust concept and it has been scaled up and optimised up to the 2 MW+ level. In the second category – the variable speed system – the use of power electronic converters enables decoupling the grid frequency from the real-time rotational frequency as imposed by the instantaneous wind speed and the wind turbine control system. Variable speed operation enables an optimisation of the performance, reduces the mechanical loading and at the same time delivers various options for active ‘power plant’ control. An essential feature of the second main wind turbine category 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.

Until the end of the 1990s, the constant speed concept was dominating the market, and it still represents a significant part of the operating wind turbine population (estimated 30% of the installed MW). It is much more

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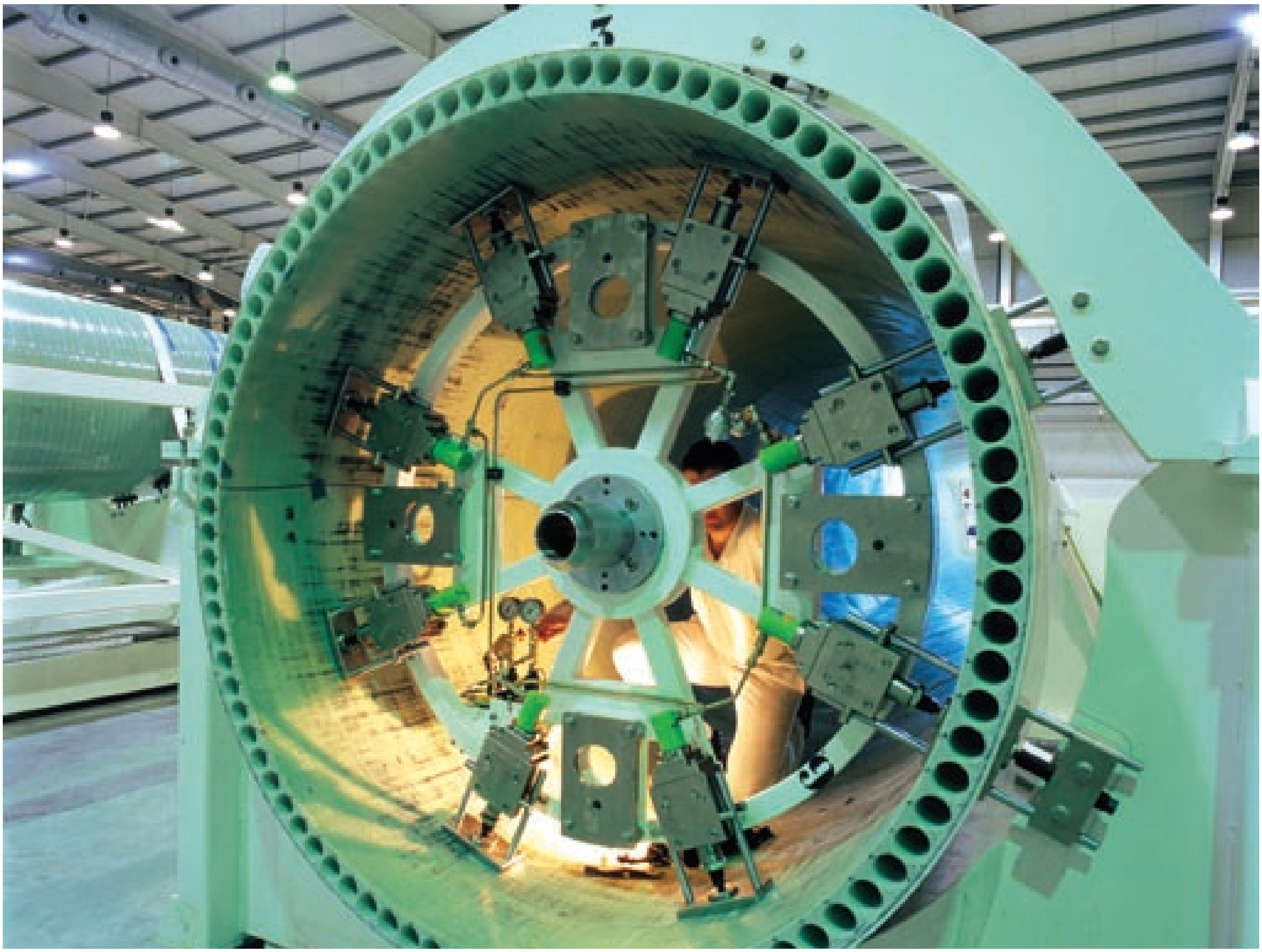
[10] For further reading the following references are recommended: ref. 1 Chapter 4, and www.windpower.org.

common now for newly installed wind turbines to belong to the second category (variable speed) wind turbines.

In view of the variety in the market, it is useful to characterise the 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 (Table 3).

In 1998, the share of the controllable concepts (Type C and D) was still limited, approximately 42% of the annually added capacity, but this has been increased to more than 80% of the total capacity sold by 2004. This shows the efforts of the industry to adapt the design to the requirement of improved grid compatibility with increasing wind power penetration. This is further explained in section 5.3. Of the total installed and operating wind turbine population (worldwide) now, the share of the better controllable types is approximately 60%[11]. The share in the world market of each type is indicated in Table 3. Because of historical (time of strong market growth), commercial (market position of manufacturers) and technical factors (e.g. grid codes) there can be large regional differences in the distribution of the types in particular regions or countries. For example, in Spain[12] the distribution is: Type A 34%, Type C 61%, Type D 5%.



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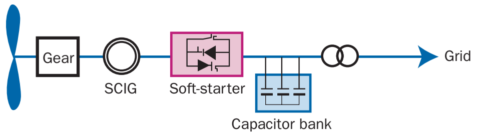
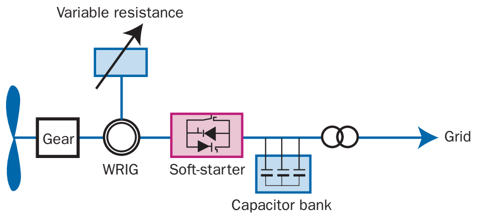
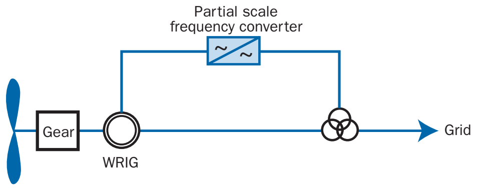
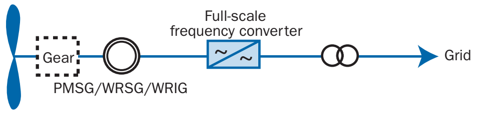
[11] Own estimation based on market reviews by BTM Consult and EER

[12] Based on data from AEE (Spanish wind turbine manufacturers association)

Table 3: Overview of wind turbine concepts

Type of system	Description
A Fixed speed (one or two speeds)  **European market share (cum):** 30%.	Introduced and widely used in the 80s, the concept is based on a 'squirrel cage' asynchronous generator (SCIG), its rotor is driven by the turbine and its stator is directly connected to the grid. Its rotation speed can only vary slightly (between 1% and 2%), which is almost "fixed speed" in comparison with the other wind turbine concepts. The concept exists both in single speed and double speed versions. The double speed operation gives an improved performance and lower noise production at low wind speeds. Aerodynamic control combined with type A concept is mostly passive stall, and as a consequence there are few active control options, besides connecting and disconnecting, especially if there is no blade pitch change mechanism. The concept has been continuously further developed, for example in the so-called active stall designs, where the blade pitch angle can be changed towards stall by the control system. **Manufacturer:** Suzlon, Nordex, Siemens Bonus, Ecotècnia **Power plant capabilities:** Voltage control, Reactive power control
B Limited variable speed  **European market share (cum):** 10%	Type B wind turbines used by Vestas in the 80s and 90s are equipped with a 'wound rotor' induction generator (WRIG). Power electronics are applied to control the rotor electrical resistance, which allows both the rotor and the generator to vary their speed up and down to ± 10% during wind gusts, maximising power quality and reducing the mechanical loading of the turbine components, (however at the expense of some minor energy losses). The wind turbines of type B are equipped with an active blade pitch control system. **Manufacturer:** Vestas (V27, V34, V47) **Power plant capabilities:** Voltage control (power quality)
C Improved variable speed with DFIG  **European market share (cum):** 45%	Type C concept is presently the most popular system, combining advantages of previous systems with advances in power electronics. The induction generator has a wound rotor, which is connected to the grid through a back-to-back voltage source converter that controls the excitation system in order to decouple the mechanical and electrical rotor frequency and to match the grid and rotor frequency. The application of power electronics provides control of active and reactive power, enabling active voltage control. In this type of systems, approximately up to 40% of the power output is going through the inverter to the grid, the other part is directly going to the grid, and the window of speed variations is approximately 40% up and down from synchronous speed. **Manufacturer:** GE (1.5 series and 3.6), Repower, Vestas, Nordex, Gamesa, Ecotècnia, Ingetur, Suzlon **Power plant capabilities:** Reactive power, Voltage control, Fault ride through
D Variable speed with full-scale frequency converter  **European market share (cum):** 15%	Type D wind turbines are offered with the classical drive-train (geared), in the direct-drive concept (with slow running generator) and even in a hybrid version (low step-up gearbox, and medium speed generator). Various types of generators are being used: synchronous generators with wound rotors, permanent magnet generators and squirrel cage induction generators. In type D wind turbines the stator is connected to the grid via a full-power electronic converter. The rotor has excitation windings or permanent magnets. Being completely decoupled from the grid, it can provide an even more wide range of operating speeds than type C, and has a broader range of reactive power and voltage control capacities. **Manufacturer:** Enercon, MEG (Multibrid M5000), GE (2.x series), Zephyros, Winwind, Siemens (2.3 MW), Made, Leitner, Mtorres, Jeumont **Power plant capabilities:** Reactive power, Voltage control, Fault ride through

SCIG:	squirrel cage induction generator
WRIG:	wound rotor induction generator
PMSG:	permanent magnet synchronous generator
WRSG:	wound rotor synchronous generator

b. Wind farm concepts

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. Until now, the emphasis in wind farm design has been mainly on efficient and economic energy production, respecting the regulations of the grid operators. With increasing wind power penetration the demands of the grid operators are changing. In response to these demands, beside energy generation, modern wind turbines and wind farms are developing towards the concept of so-called WEPP (wind energy power plant) or VPP (virtual power plant, ref. 72). The concept essentially is a wind farm with power plant properties, with the exception that the fuel supply 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 (see paragraph 4.4.4). Its control system is designed such that the power can be actively controlled, including ramping up and down similarly to conventional generation plants. Wind power plants can and do positively contribute to system stability, fault recovery and voltage support in the system.

More aspects of this concept – the major elements of which are already available from several wind turbine manufacturers – are being discussed in paragraph 5.4. The new offshore wind farms are to a large extent designed according to the principles of WEPP. An example of such a wind farm equipped with a central wind farm controller is the 160 MW offshore wind farm Horns Rev near the West coast of Denmark (see box).

Innovative offshore wind farm integration in Denmark

The offshore wind energy power plant at Horns Rev is a demonstration project to test different techniques and adjust the demands on the turbines. The wind energy power plant at Horns Rev is designed by Elsam and comprises 80 turbines each with a doubly-fed induction generator of 2 MW, i.e. a total of 160 MW. The pitch-controlled turbines have a rotor diameter of 80 m and a hub height of 70 m. The wind energy power plant is connected at the 34 kV side to an offshore HV 150/34 kV substation. A 150 kV submarine cable to Oksby and from there a land cable transport the power to the substation of Karlsgaarde. The turbines have equipment installed so they are able to stay connected to the grid in case of a grid fault. The turbines can stay connected with voltage drops down to about 15% of the nominal value.

The wind farm is provided with a special Wind Farm Main Controller (WFMC) developed by Elsam Engineering. This WFMC takes care of the entire wind energy power plant's control functions.

The production of the wind farm at Horns Rev is controlled centrally for the entire wind energy power plant according to the following requirements for the control functions:

- Production limitation, where it is possible to cap off the maximum power output.
- Reserve, where it is possible to operate the wind energy power plant with a certain reserve capacity in relation to the possible output.
- Balance control where the production can be adjusted downwards or upward in steps.
- Grid protection interventions where the output can be adjusted downwards in case of critical situations in the grid.
- Gradient limitations where it is possible to limit how fast the output will increase when the wind speeds up.

The actual output as compared to the possible output is measured on a regular basis. The reactive power can be controlled centrally with the main controller or for each turbine according to the principles agreed, with limits for intake and consumption. The control of the reactive power is limited by the fact that it must respect the allowed control range for the turbines and that it may not limit the active power production.

The wind farm's participation in frequency control is handled centrally with the main controller. In addition, the reactive power can be controlled locally so that the wind energy power plant's total consumption/intake of reactive power is kept within ±16 MVAr at the 34 kV-side of the wind farm transformer if the central control is not connected. Disconnection of the turbines in case of grid faults or too strong winds is also controlled individually. The turbines are set in such a way that they do not disconnect simultaneously at high wind speeds.

3.2.2 Wind power performance indicators

Wind turbines differ from conventional power generators in that their performance depends on the characteristics (mainly the local wind climate) of the site where they are erected. The rated power, the nameplate power, is the maximum power reached only 1 to 10% of time. Most of the time wind turbines operate at partial loads, depending on the wind speed. From the power system point of view, wind turbines can be regarded as production assets with an average power (25 – 30% of rated) and sometimes 3…5 times higher peaks.

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Wind displaces both energy and capacity in the system

Wind turbines – similarly as the other generators in the system – have two main functions that constitute their value in the power system:

- they generate (electrical) energy, their primary function that can be paraphrased as the workhorse function and expressed in GWh (units of electrical energy);
- they contribute to the system capability to match the power demand at every moment, to keep the lights on: the capacity function that can be paraphrased as the muscle function and expressed for example in GW (power units).

A key parameter indicating the electrical energy generating value of a generator in the system is the load factor (same as capacity factor). The load factor – the ratio of average generated power and rated power – of a generator is a measure for the amount of energy that can be produced per MW generating capacity (or rated capacity).

By its ‘energy’ or workhorse function, a wind power plant is capable of avoiding energy to be generated by other plants in the system, for example conventional generators. Load factors (capacity factors) of typical conventional plants vary between 50 and 90%. Typical aggregated load factors (annual average) of wind power (onshore) are in the range of 20 - 35%, depending primarily on wind climate, but also wind turbine design (rotor size with respect to generator size). As a result, from the energy generating point of view, per MW of wind power generating capacity (also called rated power), the energy generated by 0.2 MW – 0.7 MW conventional power is displaced (with the effects on fuel and emissions saved depending on the generation mix). The range is wide because it depends on many parameters, and the numbers should be judged with care.

The key parameter for the capacity function (or muscle function) of wind power plants in the system is the ‘capacity credit’. This parameter is used to indicate – on power system level, national or regional – how much of the installed wind power capacity can be considered as ‘firm’ power, that can be counted upon together with the other generators to meet the peak demand without compromising system reliability. Chapter 7 will explain that per MW of wind power, a capacity credit of 0.1 – 0.35 MW can be added. This number does not represent a substitution of other fuels; it should not be confused with the load (capacity) factor as above. Wind power capacity credit in a system depends upon many factors as will be explained in Chapter 7, so again the number should be used with care.

It will also be shown in Chapter 7 that there is no need to back up wind MW for MW, because wind power participates together with a lot of partners in a system that is designed to deal with highly variable power supply and demand. On the contrary, it will be demonstrated that only a small fraction of the generation capacity available in the system needs to be re-allocated and re-scheduled sometimes to accommodate wind power. In other words, wind turbines supply firm capacity.

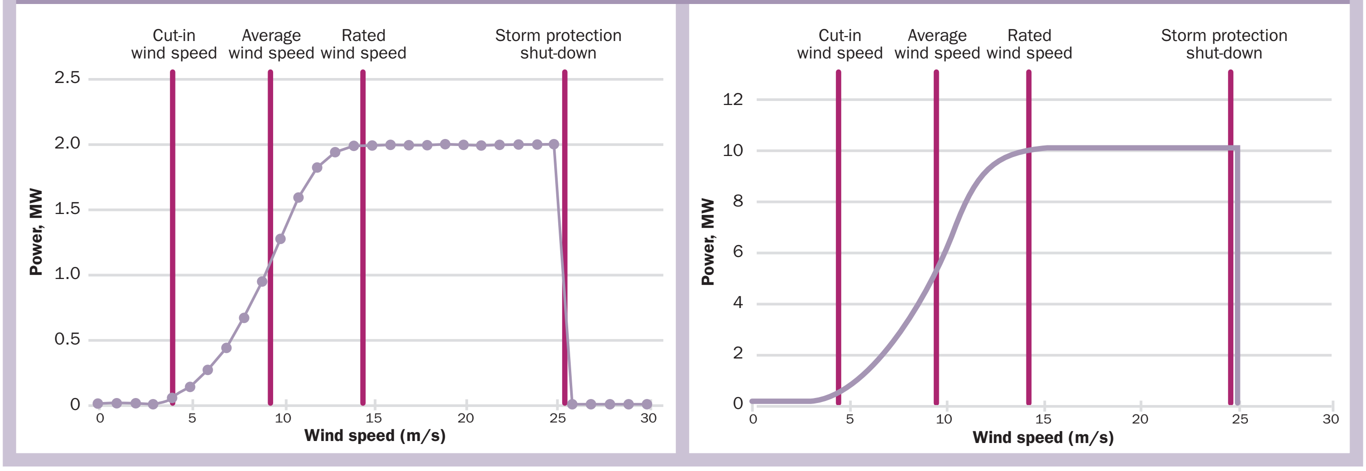
Wind power performance indicators are related to the principal wind turbine specifications, i.e. rated power, and rotor diameter. The specific rated power[13] is in the range of 300 – 500 W/m^2, where the area is the "swept area" of the rotor.

Wind turbine electric power output is measured according to IEC 61400-12 (ref. 44) and is represented in a power curve (Figure 1). The power curve is used to estimate the energy output at well-defined site-specific wind regimes (characterised in hub height wind speed and wind direction long-term frequency distribution). The energy output is standardised to long-term[14] 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.

© Nordex

Figure 1: Wind turbine power curve and aggregated wind farm power curve used e.g. for regional assessments and forecasts



Source: ref. 41

Source: ref. 79

Typical values of today installed wind turbine technology (individual wind turbine and wind farm) are given in Table 4 and Table 5.

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[13] Ratio between the wind turbine swept area (proportional to the primary wind energy capture) and the nameplate power output

[14] Long-term: indicative time scale is wind turbine technical design life time i.e. 20 years

Table 4: Wind turbine characteristics (extracted from market information and operational statistics)

Wind turbine characteristic	<Range>, Typical value
Rated power (MW)	<0.850 – 6.0>, 3.0
Rotor diameter (m)	<58 – 130>, 90
Specific rated power (W/m^2)	<300 – 500>, 470
Capacity factor (=load factor)* (%)	<18 – 40>
Full load equivalent* (h)	<1800 – 4000>
Specific annual energy output** (kWh/m^2 year)	<600 – 1500>
Technical availability*** (%)	<95 – 99>, 97.5

* depends largely on site average wind speed and on matching of specific power and site average wind speed
** normalised to rotor swept area, depending on site average wind speed
*** values valid onshore, including planned outages for regular maintenance

Table 5: Wind farm characteristics

Wind turbine characteristic	<Range>, Typical value
Rated wind farm sizes (MW)	<1.5 – 500>
Number of turbines	1 – up to hundreds
Specific rated power offshore (MW/km^2)	<6-10>
Specific rated power onshore (MW/km^2)	<10-15>
Capacity factor (=load factor)* (%)	<18 – 40>
Full load equivalent* (h)	<1800 – 4000>
Specific annual energy output offshore** (GWh/km^2 year)	<30 - 40>
Specific annual energy output offshore** (GWh/km^2 year)	<20 – 50>
Technical availability*** (%)	<95 – 99>, 97

* depends largely on site average wind speed and on matching of specific power and site average wind speed
** per km^2 ground surface
*** values valid onshore, including planned outages for regular maintenance

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3.3 Variability of wind power production

3.3.1 Wind power is a variable-output source

Wind power fluctuates over time, mainly under the influence of meteorological fluctuations. The variations occur on all time scales: seconds, minutes, hours, days, months, seasons, years. Understanding these variations and their predictability is of key importance for the integration and optimal utilisation in the power system. Electric power systems are inherently variable regarding both demand and supply and are designed to cope with it in an efficient way. The electrical demand is highly variable, dependent on a large number of factors, such as the weather, daylight conditions, factory and TV schedules etc. 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. How this is done is explained in Chapter 4.

■ Variable-output versus intermittency

Wind power is sometimes incorrectly considered as an intermittent energy source. This is misleading. At power system level, wind power does not start and stop at irregular intervals (which is the meaning of intermittent). On the contrary, at power system level, wind power never disappears from the grid 'just like that', as further explained in this Chapter. Even in extreme events such as storms it takes hours for most of the wind turbines in a system area to shut down, as will be explained in par. 3.3. Moreover, periods with zero wind power production are predictable and the transition to zero power is gradual over time. The larger the area considered, the more gradual this transition to zero, and in the limit wind power has a certain contribution to base load, with a very low probability of outage (see also Chapter 7 on contribution of wind to security of supply). **It is also worthwhile considering that the technical availability of wind turbines is at a very high level (98%), compared to other technologies. Thus, the term intermittent is inappropriate for system wide wind power and the qualifier 'variable-output' for wind power should be used.**

On the other hand, the system is prepared to deal with intermittencies such as outages of conventional plants and line faults. For thermal-generating plants the loss due to unplanned outages represents on average 6% of their energy generation (ref. 47). Detailed analysis shows that **the forced outage rate[15] of fossil plants represents at least 10%.** Thus, unplanned outages of conventional plants occur frequently. In general these forced outages are not predictable, with high gradient from full power to zero power. Conventional plants with capacities of over 1,000 MW can trip. For example, the largest single thermal unit on the UK system is 1,320 MW. In addition, the whole system continuously has to handle demand variations which often are not predictable.

Power systems are designed to deal with large variations in the supply/demand balance by having access to reserve capacity and interconnection.

■ Short and long-term variations

For grid integration purposes, the **short-term variability** of wind power (order of magnitude minutes to hours) is important because it affects the scheduling of the generation units and balancing power and the determination of reserves needed. The short-term variability of wind power experienced in the power system, is determined by short-term wind variations (weather patterns), and the geographical spreading of the wind power plants. The total variability experienced in the power system is determined by simultaneous variations in loads, all wind power plants, and other generation units. **The impact of the short-term variation on a power system depends – besides upon the amount of wind power capacity –** on the generation mix and on the long-distance transmission capacity.

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[15] Percentage of time not available due to forced outage

The **long-term variability** of wind power (characteristic time scale: months, years) is determined by seasonal meteorological patterns and by inter-annual variations of the wind. In certain regions this can also depend on the market growth of wind energy. This variability characteristic of wind hardly affects system operation. In the long term it determines the capacity credit of wind power in the system (see Box and Chapter 7) and has to be taken into consideration in long-term power system planning.

3.3.2 Short-term variability

Analysis of available data from operating wind farms and meteorological measurements at typical wind farms locations allows us to quantify the variations in net power output that can be expected for a given time period, i.e. within the minute, within the hour or over several hours. The distinction between these specific time scales is made because this type of information corresponds to the various types of power plants for balancing.

The results from analyses show that the power system handles this short-term variability rather well. System operators only need to deal with the net output of large groups of wind farms, and the wind power variability has to be viewed in relation to the level and variation in the power demand. Variations within the hour are not easy to forecast, but are smoothed out to a great extent when considering a larger area. Hourly, 4-hourly and 12-hourly variations can be forecasted to a great extent, and can be taken into account when scheduling power units to match the demand. In this time scale it is the uncertainty of the forecasts that cause balancing needs, not the variability itself.

From data analysis of operational wind farms, the following can be observed:

- For large individual wind turbines, the variation in the power output on seconds scale is very small, due to the averaging of the wind field across the rotor and the filtering effect of the turbine inertia.
- For an individual wind farm, the variation in the aggregated power output is small for time-scales of tens of seconds, due to the averaging of the output of individual turbines across the wind farm.
- For a number of wind farms spread across a large area such as a national electricity system, the variation in the total power output of all wind farms is small for time-scales from minutes or less, up to tens of minutes. This is the "geographic diversity" effect.

■ Within the minute

The fast variations (seconds…minute) of aggregated wind power output as a consequence of turbulence or transient events are quite small as a result of aggregation and are hardly felt by the system.

■ Within the hour

The variations within an hour – 10…30 minutes – are much more significant for the system; however they should always be considered in relation to the demand fluctuations. These variations even out to a great extent with geographic diversity, and will generally remain inside ±5% of installed wind power capacity for geographically distributed wind farms (ref. 135 Ireland). The variations in wind speed produce the most significant variations in power output at 25 – 75% of rated power[16]. Extreme variations can be controlled at critical times by measures such as setting a temporary cap on the output of all wind farms, or by limiting 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 eminently controllable in this respect. Clearly, limiting the output of wind generation wastes "free" energy and should only be done when other means have been exhausted. The operational aspects of wind farms and the power system are further dealt with in Chapter 4.

The largest variations come from passage of storm fronts, when wind turbines reach their storm limit and shut down from full to zero power in minutes. This is in general significant only when one considers relatively small geographical areas. For larger areas it takes hours for most of the wind power capacity to disappear in a storm. Example: for the storm in Denmark on 8.1.2005 – one of the biggest storms Denmark has

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[16] In this power output range, the slope of the power curve is the largest

seen in decades – it took 6 hours for the 2400 MW wind power in West Denmark area (200 km^2) to drop from 2000 MW to 200 MW. The loss of a concentrated offshore wind farm could happen within an hour. If most of the capacity comes from concentrated large offshore wind farms a control method of not shutting down the turbines completely in storms is recommended. The passage of a storm front can be predicted and appropriate control can be adopted to minimise the effects.

Summing up: In 10…30 minute time scale the variations will remain inside ±5% of installed wind capacity most of the time. This will be an issue for power system reserves for balancing when wind power penetration reaches the extent where the variations are comparable to variations in demand (when 5…10% of yearly electricity demand is produced by wind power).

■ Hourly variations

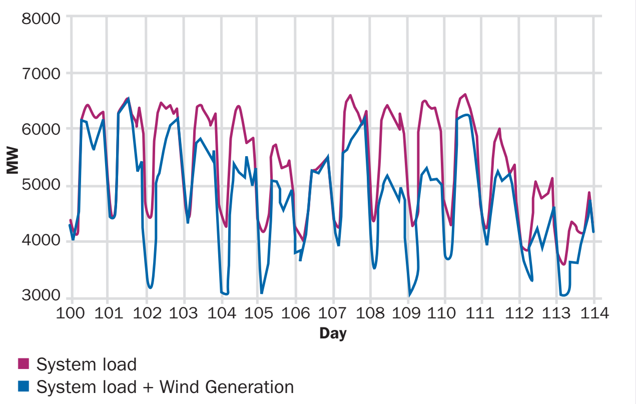
The variations several hours ahead affect the scheduling of the power system and these can be predicted using a wind power prediction tool. For system operation, the variation in itself is not so much of problem. It is the uncertainly of how accurately the variation can be predicted or not that matters. Again, the uncertainty of wind power predictions should always be considered in relation to the errors in demand forecasts. There is much work being conducted on this issue showing that solutions are available.

The extent of hourly variations of wind power and demand are shown in Table 6. It is useful to express these wind power variations as a percentage of the installed wind power capacity. Extensive studies have been done in Denmark, Germany and UK, and an overview of the conclusions is given in Table 6.

Table 6: **Largest variations of wind power (with respect to size of the area considered and (ref. 2) for different time periods (hourly and 4-12 h variations)**

Area size (km x km)	Largest variation % (up or down)	Example
Hourly variations		
100 x 100 km	50	UK (ref. 28)
200 x 200 km	30	Denmark (ref. 2)
400 x 400 km	20	Germany, Denmark, Finland
Group of countries	10	
4-12 hour variations		
One country	40 – 60 80	Denmark Germany
Larger area	35	Nordic area (ref. 2)
400 x 400 km	4h: 80% 6h: 80% 12h: 90%	United Kingdom (ref. 28)

Figure 2: Typical variations of system load with and without wind power (UWIG, 2005). The capacity penetration as a % of peak load is 15%. This is a 14 day period from an annual simulation from a study of the Xcel-North system in Minnesota for the year 2010. The annual energy penetration was 11.5%.



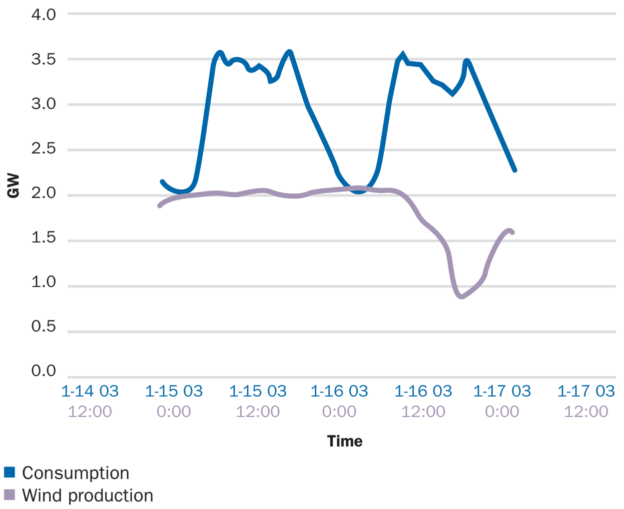
Source: UWIG, 2005, ref. 46.

Extreme cases for system operation are large variations, up or down, that have been wrongly predicted, e.g. a storm front with uncertainty about how much wind power generation will be reduced as a result of it. Here, prediction tool accuracy is of primary importance, as will be discussed further in Paragraph 3.4 and Chapter 4. It should be remarked that technical solutions are available to reduce the steep gradient when a storm front is passing a wind farm – for example by providing wind turbines with storm control[17] – as for instance used by Enercon.

3.3.3 Long-term variability

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

Figure 3: Example of wind power and system load variation over two days in the winter of 2003. The wind power production is from 5000 distributed sites. The system load includes the effect of cross border exchange



Source: Eltra

■ Monthly and seasonal variations

The monthly and seasonal variations are of importance for:

- Electricity traders. They have to deal with electricity forward contracts and wind power volume has an influence on the price. Statistics as presented in Figure 5 provide valuable insights, which show the monthly variations of aggregated wind power on system level in Germany.
- Planning of the power system. The contribution of wind power to system security is the so-called capacity credit of wind power. The capacity factor during high load periods is a measure for the capacity credit for low wind power penetration levels (see also Chapter 7). The system operators may use these expected capacity factor values as an input parameter in the adequacy forecasts.

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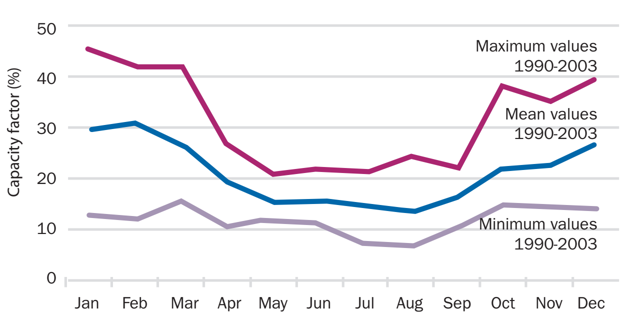
[17] With Enercon storm control – instead of shutting down the wind turbine above cut-out, the power curve above cut-out wind speed (25 m/s) decreases gradually to reach zero power at 35 m/s.

It can be seen that monthly wind power variations lay within a narrow band during summer months, especially in May and September. In both the electricity trading area and for system planning purposes, the deviations can be sufficiently hedged.

Figure 4: Average, maximum and minimum values of monthly capacity factors. (Germany 1990-2003)

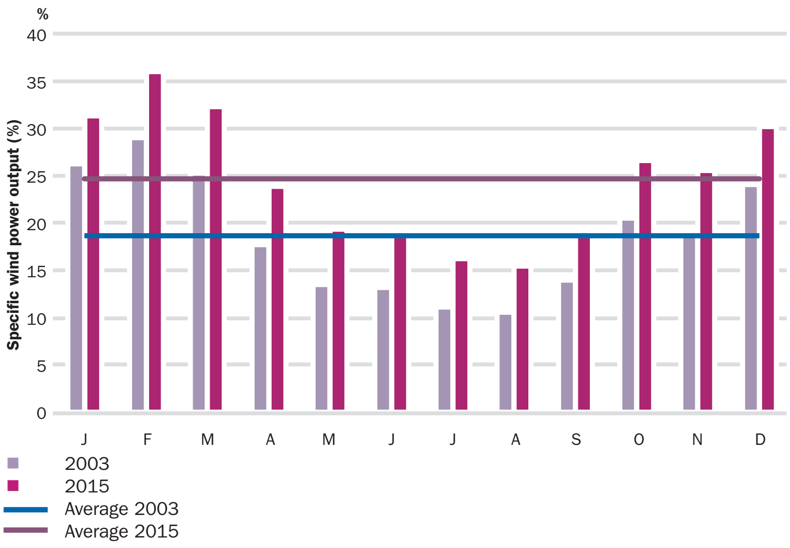


Source: ref. 25, ISET 2004

■ Annual variations

Analysis of at least 30 years of data from sites all over Europe (ref. 48) indicates that the annual variability of long-term mean wind speeds at sites across Europe tends to be similar and can reasonably be characterised by a normal distribution with a standard deviation of 6%. It was concluded that results vary little from location to location. The same trend was observed for the rest of the world, in Australia, Japan and the US. The result is useful in order to determine the expected variation in long-term wind behaviour and the corresponding annual energy output of wind power projects. The inter-annual variability of the wind resource is less for example than the variability of hydro inflow. And last but not least: on a power system level the annual variations are influenced by the market growth of wind power and by the projected ratio onshore/offshore.

Figure 5: Monthly capacity factors of the German wind power generating population. The graph illustrates that the average load factor is expected to increase significantly in the time span from 2003 to 2015 as a consequence of technical improvements and an increasing share of offshore installations



Source: DENA 2005

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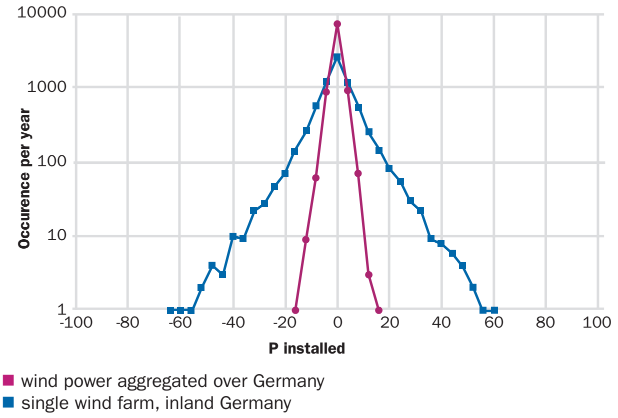
3.3.4 Effects of aggregation and geographical dispersion

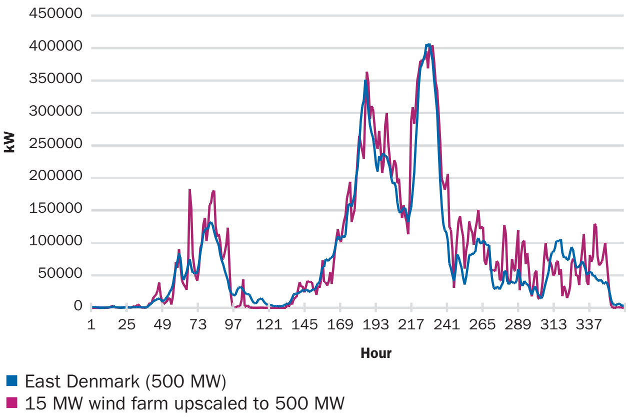
With a wide regional distribution of wind turbines, short-term and local wind fluctuations are not correlated and therefore largely balance out each other. This phenomenon has been extensively studied throughout Europe, see for example ref. 148. As a result the maximum amplitudes of wind power fluctuations experienced in the power system are reduced. This smoothing effect is illustrated in Figure 6. In this example from Germany, the frequency of occurrence of positive and negative changes observed in the hourly values of wind power output is obtained from measured outputs of wind farms. The figure shows that the frequency distribution is becoming much smaller for the larger area, which means that the amplitudes of the variations are decreasing. Whereas a single wind farm can exhibit (hour to hour) power swings of up to 60% of capacity, the maximum hourly variation of 350 MW of aggregated wind farms in Germany does not exceed 20% (ISET). For larger areas, such as the Nordel system which covers four countries, the largest hourly variations would be less than 10% of installed wind power capacity, if the capacity was distributed throughout all the countries (ref. 2). **Geographical spread of wind farms across a power system is a highly effective way to deal with the issue of short term variability. Put in another way, the more wind farms that are in operation, the less impact from variability on system operation.**

Figure 6: Frequency of occurrence of hourly wind power variations and the effect of geographical aggregation.



Source: ISET

Figure 7: Example of smoothing effect by geographic dispersion. The figure compares the hourly output of 500 MW wind power capacity in two situations, calculated from observed data in Denmark. The red line shows the output of a single site, scaled up to 500 MW. The blue line shows the multiple site output.



Source: ref. 49

In addition to the advantage of reducing the fluctuations, the effect of geographically aggregating wind farm output is an increased amount of firm wind power capacity in the system. **In simple terms: wind always blows somewhere. Also, the wind never blows very hard everywhere at the same time.** The peaks of wind power production are reduced when looking at a larger area, which is important as absorbing power surges from wind turbines is challenging for the system. The effect increases with the size of the area considered. Ideally, to maximise the smoothing effect, the wind speeds occurring in different parts of the system should be as uncorrelated as possible. Due to the typical sizes of weather patterns, the scale of aggregation needed to absorb a storm front is in the order of 1500 km (ref. 130). By aggregating wind power Europe wide, the system can profit from the complementarity of cyclones and anticyclones over Europe (Figure 8). The economic case for smoothing wind power fluctuations by utilising transmission capacity (rather than by other means) is not yet obvious and will be an important area of investigation in the near future (refs. 55, 115, 130).

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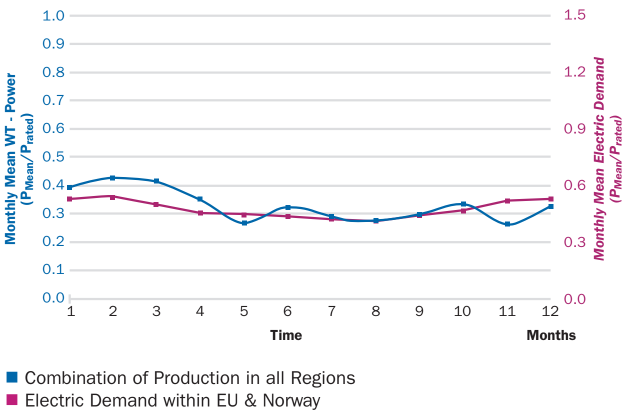
Figure 8: Combining wind energy production from Europe and Northern Africa (Morocco) results in a monthly pattern that matches well with the demand in Europe and Norway

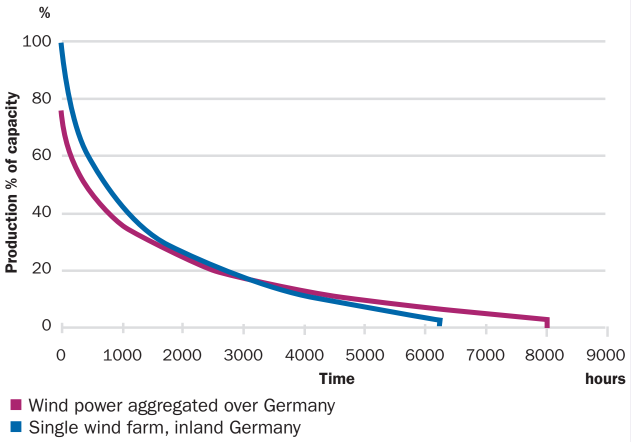


Source: Czisch 2001, ref. 50

A method to represent the effect of aggregation on system scale is the load duration curve of wind farms, which gives the frequency distribution of the partial load states of generated wind power. Examples for Germany and the Nordic area are given in Figure 9 and Figure 10. The effect of aggregating the wind power is a flattening of the duration curve. In practical terms: when wind power is aggregated over a large area, the effective number of hours where wind power is available increases, while the maximum value of instantaneous aggregated power produced is decreasing.

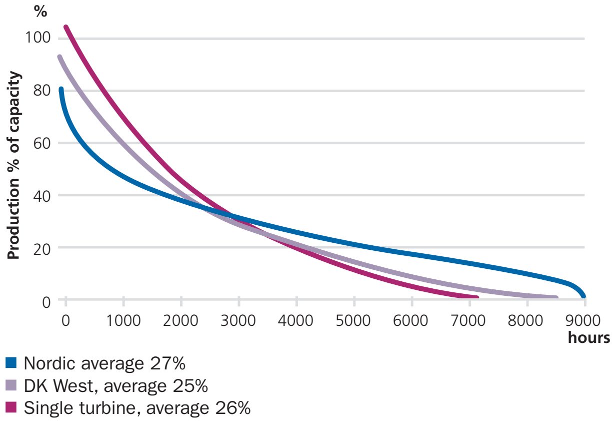
Large-scale wind power cannot be aggregated to an optimal extent without a well interconnected grid. In this perspective, the grid plays a crucial role in aggregating the various wind farm outputs installed at a variety of geographical locations, with different weather patterns. The larger the integrated grid – especially beyond national borders – the more pronounced this effect becomes. This effect is exactly analogous to the use of the grid to aggregate demand over interconnected areas.

Figure 9: Duration curves for the 'wind year 2003', Germany



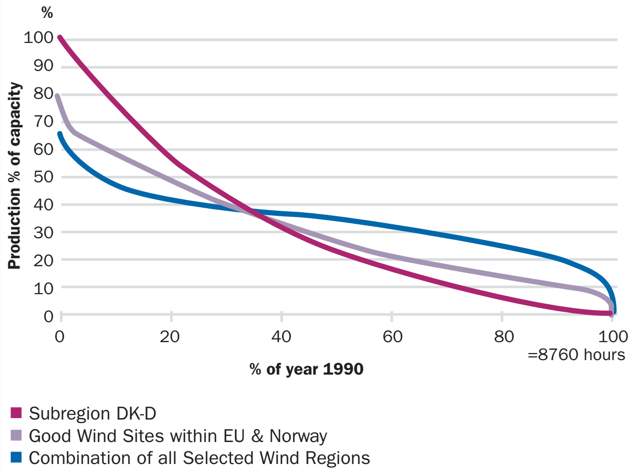
Source: ref. 25, ISET 2004

Figure 10: Duration curves for the 'wind year 2000', Denmark and Nordic countries, assuming equal wind capacity in each of the 4 countries



Source: ref. 2

Figure 11: Smoothing effect of aggregation 'European' wind power with wind power from regions outside Europe, notably North Africa



Source: Czisch 2001, ref. 50

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3.4 Variability versus predictability of wind power production

3.4.1 General

Accurate forecasts of the likely wind power output in the time intervals relevant for scheduling of generation and transmission capacity allow system operators and dispatch personnel to manage the variability of wind power in the system. Predictability is the key to wind power's variability. The quality of the wind power prediction has a beneficial effect on the magnitude of balancing reserves needed. Thus, forecasting of wind power is important for its economic 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 5-min to hour intervals over periods up to 48-72 hours in advance and for seasonal and annual periods. These tools are described in par. 3.4.2.

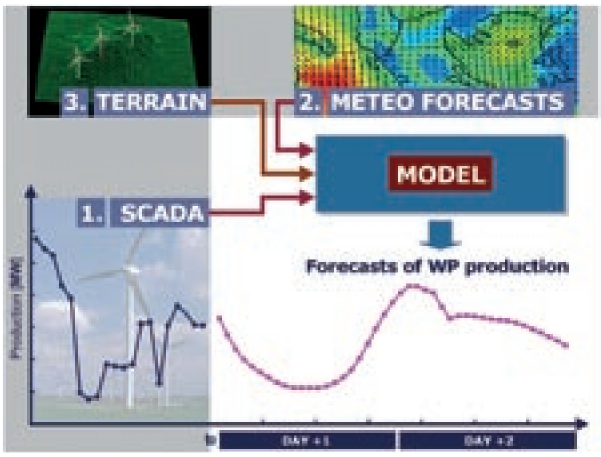
Forecasting wind power production is a different task from the forecasting other generation forms or forecasting the load[18]. **Wind, being a natural phenomenon, is more amenable to reliable statistical treatment and physical forecasting than conventional plant which is subject mainly to physical faults.** There is extensive experience with demand (load) forecasting, and consumption is more predictable than wind power. The quality of wind power forecasts is discussed in 3.4.3, where it will be explained how wind power prediction accuracy improves at shorter forecast horizons and when predicting for larger areas.

3.4.2 Forecast tools

Short-term wind power prediction consists of many steps (ref. 51). For a forecasting horizon of more than 6 hours ahead, it starts with a Numerical Weather Prediction (NWP) model (see Box), which provides a wind prognosis, i.e. the expected wind speed and direction in a future point in time. Further steps are the application of the NWP model results to the wind farm site, the conversion of the local wind speed to power, and the further application of the forecast to a whole region.

There are different approaches to forecasting wind power production, typically models that rely more on physical description of the wind field and models that rely on statistical methods. Figure 12 clarifies the relationship between statistical and physical models, as both can appear in an operational short-term forecasting model.

Figure 12: Overview of various forecasting approaches (ref. 51). The variety of forecast techniques have in common that wind data are provided by a weather forecast and production data are provided by the wind farms. The two data sets are combined to provide a forecast for future energy production.



The various forecasting approaches can be classified according to the type of input (SCADA indicates data available on-line) All models involving Meteo Forecasts have a horizon determined by the NWP model, typically 48 hours.

(1)	Short-term statistical approaches using only SCADA as input (horizons: < 6 hours)
(2)	Physical or statistical approaches. Good performance for >3 hours.
(2) + (3)	Physical approach. Good performace for >3 hours
(1) + (2)	Statistical approach
(1) + (2) + (3)	Combined approach

Source: G. Giebel

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[18] Except, of course, unplanned outages of conventional plant which by nature are not predictable. In this respect, wind power often has another advantage because of its modular nature and of the smaller amounts of capacity that disappear at once in case of outages.

The tools are also differentiated by their input data from the NWP model. At the very least, wind speed and direction at the wind farm are used. 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 coarse NWP model resolution, which in Europe for the current models is between 5 and 15 km horizontal resolution. In some cases with gentle terrain (for example Denmark), this resolution is good enough for wind energy. In complex terrain (for example Spain), such resolution does not capture all the local effects surrounding the wind farm. 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 farm. When using statistical models, the influence of orography on the accuracy of the outcome is less, and experience in Spain shows good results in complex terrain. The science of short-term forecasting is developing very rapidly with remarkable results.

Numerical weather forecasts, meso-scale models and grid squares

In general, 'meso-scale' weather forecast models, such as Local Model (German Weather Service), the Scandinavian HIRLAM model, the UK Met Office model, etc., deliver estimates for meteorological parameters in the form of 'grid square averages'. The term 'meso-scale' refers to the size of those grid-squares being in the order of around 0.5x0.5 up to 15x15 km^2. For each individual grid square, prediction values are provided for up to 50 height levels above ground: typically wind speed, wind direction, air pressure and air temperature.

These grid square averages can be further processed to take into account the sub-grid scale variation in the surface properties such as hills or mountains. The spatial extrapolation of meteorological data is a challenging task, especially in heterogeneous landscape. Therefore, improvements of prediction accuracy require smaller spatial resolutions.

Model improvement programmes of several European Weather Services are currently targeted towards 2-3 km grid square resolution to be reached by the end of 2006. The most advanced models will then provide values for 50 vertical levels (heights above ground), and the forecasts will be updated every 3 hours. Improved validation methods, such as remote atmospheric observation via satellite, radar and lidar will lead to even better forecast results.

Some of the major short-term wind power forecasting models available on the market are listed in Table 7. Although the current set of models for short-term forecasting starts to perform reasonably (ref. 51), intensive development work is still going on to improve the methods.

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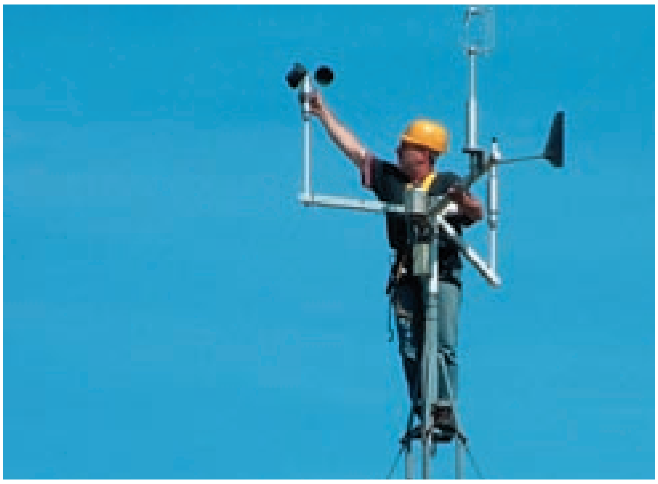
Table 7: Overview of operational short-term wind power forecast models (ref. 51 and AEE).

PREDICTION MODEL	MODEL DEVELOPER	METHOD	OPERATIONAL STATUS, REGION	OPERATIONAL SINCE
Prediktor	Risø National Laboratory* (DK)	Physical	Spain, Denmark, Ireland, Germany, (USA)	1994
WPPT	IMM, Technical University of Denmark*	Statistical	≈2.5 GW, Denmark (East and West)	1994
Previento	University of Oldenburg and Energy & Meteo Systems (DE)	Physical	≈ 12 GW, Germany	2002
AWPPS (More-Care)	Armines/Ecole des Mines de Paris (F)	Statistical, Fuzzy-ANN	Ireland, Crete, Madeira	1998, 2002
RAL (More-Care)	RAL (UK)	Statistical	Ireland	-
Sipreólico	University Carlos III, Madrid Red Eléctrica de España	Statistical	≈ 4 GW, Spain	2002
LocalPred-RegioPred	CENER (ES)	Physical	Spain	2001
Casandra	Gamesa (ES)	Physical	Spain, Portugal and USA	2003
GH Forecaster	Garrad Hassan (UK)	Physical and Statistical	Spain, Ireland, UK, USA, Australia	2004
eWind	TrueWind (USA)	Physical and Statistical	Spain (represented through Meteosim) and USA	1998
HIRPOM	University College Cork, Ireland Danish Meteorological Institute	Physical	Under development	-
AWPT	ISET (DE)	Statistical, ANN	≈ 15 GW, Germany	2001
AleaWind	Aleasoft (ES)	Statistical	Spain	2004
Scirocco	Aeolis (NL)	Physical	Netherlands, Spain	2004
Meteologica	MBB	Physical	Spain	2004
Meteotemp	No specific model name	Physical	Spain	2004

* Risø and IMM form the Zephyr collaboration.

Additionally, some of the traditional power engineering companies have shown interest in the field. This could start a trend towards treating short-term prediction models as a commodity to be integrated in energy management systems, wind farm control, SCADA systems and wind farm operation. Information and communication technology is expected to play a major role for integrating wind power prediction tools in the power market infrastructure.



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3.4.3 Accuracy of short-term wind power forecasting

Present accuracy levels

The prediction error – used for measuring the accuracy of forecasting wind power – can be quantified with different error functions. Quite common is the Root Mean Square Error (RMSE) normalised to the installed wind power. The correlation coefficient between measured and predicted power is very useful as well. Since the penalties in case of errors often scale linearly with the error, be it up or down, the Mean Absolute Error or Mean Absolute Percentage Error (for example in Spain, see par. 4.2.1.2) is also used.

Regardless of the forecasting method used, the forecast error (RMSE) for a single wind farm 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. **The forecast accuracy is reduced for longer prediction periods. 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 more efficient system operation without compromising system security. In most countries gate-closure times are set arbitrarily by system operators without any technical justification, at the expense of the electricity consumer** (see also Chapter 4).

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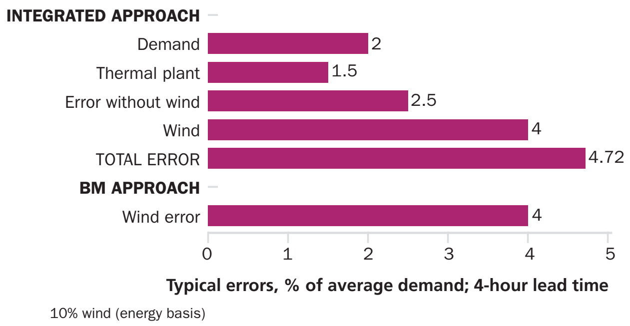
For larger areas, average errors in demand forecasting are in the order of 1.5–3% of peak load, which corresponds to an error of about 3–5% of total energy when forecasting one day ahead (ref. 2). Such accurate day-ahead forecasts cannot be obtained for wind power with currently available technology. It has to be borne in mind, however, that for system operation, the combined error of wind and load forecasting is decisive. When determining the additional system balancing requirements for wind power, only the additional deviation compared to a system without wind has to be taken into account, not the total wind forecast error. Therefore, at low penetration levels, the prediction error for wind has a small effect on the total system's prediction error. Figure 13 illustrates the combination of the different relevant forecast errors for a power system. The resulting forecast error is lower than the sum of the individual errors, because load and wind forecasts are not correlated. **In other words, 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.**

Figure 13: The total error relevant for scheduling reserves is a result of a combination of errors in demand forecasting, plant operation and wind forecasting. A balancing market (BM) approach, only looking at wind error, is over-penalising the wind prediction error, because on system level the additional reserves only have to be based on the change in combined prediction error, which in the example is 2.2%.



Source: Milborrow 2004, ref. 164

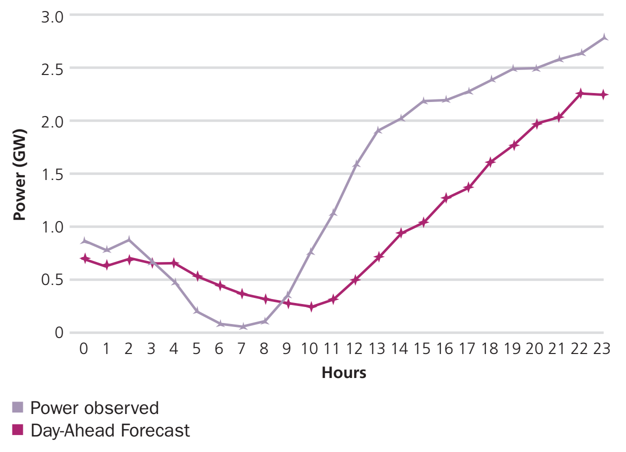
■ Comparative merits of forecasting tools

In order to establish the relative merits of a particular forecasting tool, it is necessary to compare them under the same circumstances. An extensive evaluation of the available tools for short-term forecasting has been carried out within the framework of the European Anemos project[19]. A common set of criteria was developed for measuring the performance of short-term forecast models (ref. 52). The Anemos project compared 11 models for six wind farms in four countries in Europe (ref. 53), and found that the spread between the models was site dependent, that not one single model was best in all sites, and that the mean error of all models seemed to be connected to the complexity of the terrain. In Spain, the national wind industry association AEE is assessing the performance of a range of forecast models by comparing simulation results with actual wind farm outputs[20]. In general, it is found that advanced statistical models tend to do well in most circumstances, but require training with about half a year of data before they perform very well. Physical tools, on the other hand, can have forecasts ready even before the wind farm is erected, and can later on benefit from measured data. Some physical tools however have the disadvantage that they require large computing facilities. In this case, they have to run as a service by the forecaster, while computationally less demanding models can be installed at the client's side.

■ System operator (TSO) demands on forecasting accuracy

TSOs manage the power flows and possible congestions in the grid. In order to enable TSOs to cope with the actual situation at acceptable cost, the forecast errors need to be as low as possible up to approximately 12 hours ahead. For system operators, the most critical situations are the ones where a large variation in wind power output is forecasted, but the uncertainty remains even 1-2 hours before the occasion. A start of a windy day is one example, as in Figure 14, where high wind power production was forecast. However, it did not materialise when expected. Recent practice shows that phase errors are becoming smaller as a consequence of improvement of the forecast tools. An extreme storm is another, more rare, example, with a drop of wind power production expected that may or may not come depending on how the wind speeds evolve. The proper way to address these challenges is through a combination of forecasting and wind farm control.

Figure 14: Time shift as a typical meteorological forecast error



Source: ISET

■ Forecasting accuracy versus gate-closure times

Last but not least, the quality of the short-term forecast should be considered in relationship to the gate-closure times in the power market. These times quite often have no rational technological or economic basis in the power system (ref. 57). In view of the forecast accuracy possibilities of wind power, reduced gate closure times would be more favourable. The prediction accuracy is twice as good at three hours ahead as it is at 36 hours ahead

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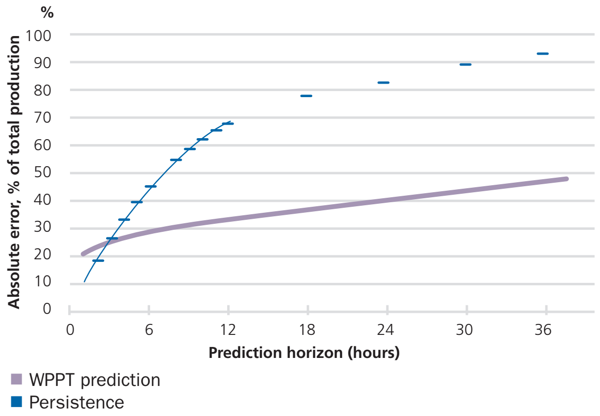
[19] ANEMOS is an EU R&D Project: (ENK5-CT-2002-00665), www.anemos.cma.fr

[20] Prediction Exercise http://prediccion-pee.com

Significantly, the quality of the short-term forecast should be considered in relationship with the gate-closure times in the power market. These times quite often have no rational technological or economic basis in the power system (ref. 57). In view of the forecast accuracy possibilities of wind power, reduced gate closure times would be more favourable and cheaper for the consumers. **Reducing the often very long gate closure times has a dramatic impact on accuracy and, hence, the cost of balancing the system.** This is illustrated in Figure 15 where the error (in energy produced) is twice as large 36 hours ahead than 3 hours ahead.

Figure 15: The total absolute prediction error (sum) during one year for different prediction horizons, as percentage of the total realised production, based on wind power prediction state-of-the-art 1997.



Source: Ref. 2

State-of-the-art prediction tool in Germany

The state-of-the-art and expected improvements of wind power prediction tools are being discussed in the Dena study (ref. 89). All German TSOs nowadays apply the Advanced Wind Power Prediction Tool (AWPT), which is based on artificial neural networks and shows respectable results. The accuracy of the prediction system is expected to further improve both in short-term and long-term horizons, as shown in Table 8. From the table it is clear that the ranges of under-estimation and over-estimation are not symmetrical. This is not without consequence: it is more economic to overproduce and sell the wind power surplus, rather than staying short and being obliged to buy expensive power on the intra-day market.

Table 8: Accuracy levels of wind power prediction in Germany

	2003	2007	2010	2015
	‘Day-ahead’ prediction			
Mean Value	-0.28%	-0.29%	-0.32%	- 0.32%
NRMSE	7.29%	6.77%	6.05%	5.91%
Max. underestimation	-27.50%	-27.50%	-24.00%	-23.50%
Max. overestimation	41.50%	39.00%	30.50%	29.50%
	‘4h’ prediction			
Mean Value	1.26%	1.16%	0.97%	0.97%
NRMSE	4.92%	4.48%	3.90%	3.89%
Max. underestimation	-17.00%	-16.75%	-14.50%	-14.00%
Max. overestimation	33.00%	28.50%	24.50%	24.25%

Source ISET report to Dena

Future expected improvements

Feedback from existing online applications continues to lead to further improvements of the state-of-the-art prediction systems.

The largest improvement potential for the accuracy of wind power prediction is in the area of weather forecast models. Weather services such as the UK Met Office, the French, the German and the Scandinavian Weather Services have announced a higher spatial resolution as well as a higher frequency of their individual numerical weather predictions (see Box). In the case of Germany, the improvement of wind power predictions day-ahead is expected to reduce the error from 7.3% down to below 6% NRMSE within the next years. There is still room for improvement in the coupling of NWP and short-term forecasting models, trying to use more and better adapted data from the NWP. A very exciting aspect of these developments is that they are not driven by the wind industry alone but by the interests of many other commercial and industrial entities – weather forecasts are improving all the time.

A current topic is the online estimation of the uncertainty. In this respect, the quantity and quality of the historical data available for each wind farm and collected through Electronic Data Interchange between wind farm and dispatch is of significant influence to prediction tools accuracy.

Another potential for improvement is combined forecasting, where data from multiple NWPs or multiple forecasting model are adaptively used.

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3.5 Summary and conclusions

■ Wind turbines and wind farms become more controllable

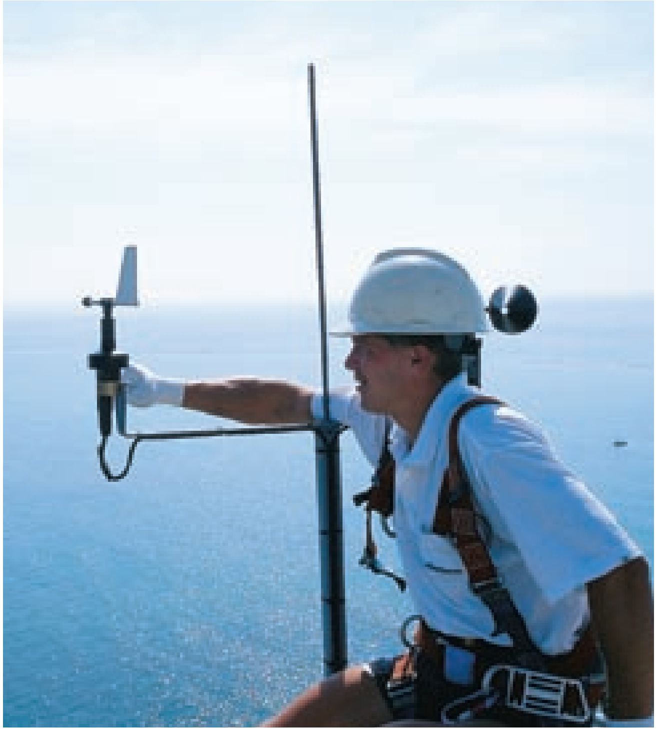
Concepts of grid-connected wind turbines have gradually been evolving in the last 25 years to MW size power generation units with advanced control systems. At present the majority of the older wind turbine types have only modest controls whereas the majority of the new turbines have active control possibilities, mainly because of the presence of active blade pitch systems, and turbine rotational speed control by power electronics. Since the wind turbine market is growing fast, controllable wind turbines now constitute the majority of the newly-installed wind power capacity. Active control includes the capability to ramp up and down in a controlled way, (wind allowing). Active power control means that the power output pattern is not only determined by the wind but also takes into account the demands of the power system. Active power control is costly from a system point of view and should only be used in situations when other more cost-effective solution in the system have been exhausted.

New technology and innovation enable wind farms of today to function as power plants (WEPP) meeting a major part of the control requirements made on traditional power plants, and to deliver part of ancillary services. **In this way, wind power plants have the ability to positively contribute to system stability, fault recovery and voltage support in the system. Whereas not necessary at low penetrations, these advanced wind farm properties will prove to be increasingly useful at high levels of wind power penetration.**

■ Understanding the variable-output character of wind power

Analysing the variability of wind power on different time scales is necessary to understand its impact on the power system. What matters for the system, firstly, are the variations within the hour (10…30 minutes). These fast variations even out with geographic dispersion and become an issue for load following reserves when wind power penetration reaches 5 – 10% penetration of gross consumption, because they become comparable with the variations in the demand. The rare occasions when these variations are extreme may be controlled at critical times by wind farm operation and control.

The second type of variation that is important for the system are the variations 1…12 hours ahead. These affect the scheduling of the power system, and can be predicted using a short-term wind power forecast tool. For power system reserves, the variations themselves are not so much the problem but the uncertainty about the magnitude of variation at a given moment is the problem. Accurate wind power forecasting can significantly diminish this uncertainty. **In the context of power system balance, wind power variability always has to be considered in relationship to the demand variability, and other supply intermittencies.**



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■ Short-term forecasting is an essential tool to manage the variability of wind power

Forecasting wind power helps to keep down the system costs of dealing with variable-output generation. The forecast accuracy can contribute to minimising the probability of an unexpected gap between scheduled and actual system load, thus avoiding last-minute deployment of expensive reserve power.

Present day accuracy levels of forecast tools for regionally aggregated wind farms are of the order of magnitude of 10% day ahead (error on power output) and 5% 1-4 hours ahead. The influence of the forecast horizon is very important. Reducing the forecast horizon from day-ahead to a few hours ahead halves the required balancing energy due to prediction errors.

Accurate methods for short term wind power forecasting are widely available as there is a whole range of commercial tools and services in this area, covering a wide range of applications and customised implementation. A common set of criteria to judge the performance of the various methods has been developed in the European research project Anemos.

Accuracy of wind power forecasting should be regarded in relation to the other system uncertainties (load and conventional generation). At low wind power penetrations (up to 5%) the effect of wind power forecast uncertainty on system reserves is small.

Further research needs to be continued to further improve the accuracy of the models but also to assess the actual uncertainty of the predictions. Besides improvement of input data from NWP, combined forecasting is a promising area. Continued collecting feedback from existing on-line applications is required to lead to further improvements of the prediction systems.

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4 Operating power systems with a large amount of wind power

4.1 General

In order to integrate wind power efficiently at higher levels of penetration, changes are necessary in the methods of operating various parts of the power system – such as generators and transmission systems. Moreover, active management at the demand side of the power system can be used to facilitate wind power integration. Wind power with its variable output characteristics affects the other generators in the system. Besides reducing their required output, wind power necessitates a different way of scheduling the other plants in the system. Paragraph 4.2 explains the principles of system operation with wind power, from a generation point of view and gives generalised results and details from national/regional studies on required balancing capacities and costs. It is explained how both the power systems inherent flexible mechanisms and wind power predictability mean that wind power does not need to be backed up in the system MW for MW. Paragraph 4.3 addresses system operation from the viewpoint of the system operator.

Paragraph 4.4 describes options for managing the additional variability in the system due to large-scale wind power by increasing the system flexibility.

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4.2 Generation and reserves/balancing issues

If significant new wind generation is added to the power supply, its impacts – just like for any other major power source — extend to all relevant time scales (see box): seconds, minutes, hours and days. These impacts are expressed in terms of (relative) extra reserve power required, consequences on the power cost and measures to be taken in the technical operation and in the power market redesign in order to integrate the wind power in an economic and orderly way.

It has to be emphasised 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 (i) in demand, and (ii) in generation from conventional and renewable generation. These individual fluctuations are generally not correlated, which has an overall smoothing effect with a consequent beneficial impact on system cost.

The operational routines of system operators vary in different synchronous systems and also in different countries. Also the terminology of the reserves used varies. In this report, we generalise the reserves to two groups depending on the time scale: 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 (see box and Figure 16). 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 these two).

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Principles of power balancing in the system

In power systems, the power balance between generation and consumption must be continuously maintained. The essential parameter in controlling the energy balance in the system is the system frequency. If generation exceeds consumption, the frequency rises; if consumption exceeds generation, the frequency falls. Ultimately, it is the responsibility of the system operator to ensure that the power balance is maintained at all times.

Power system operation covers several time scales, ranging from seconds to days. To start with, primary reserve is activated automatically by frequency fluctuations. Generators on primary control respond rapidly, typically within 30-60 seconds. Such imbalances may occur due to the tripping of a thermal unit or the sudden disconnection of a significant load. The immediate response from primary control is required to re-instate the power balance, so that the system frequency is at a stable value again. For this near-immediate response to power imbalances, sufficient generation reserves must be available by generation units in operation. Secondary reserve is active or reactive power activated manually or automatically in 10 to 15 minutes after the occurrence of frequency deviation from nominal frequency. It backs up the primary reserve and it will be in operation until long-term reserves substitute it as seen from Figure 16. The secondary reserve consists of spinning reserve (hydro or thermal plants in part load operation) and standing reserve (rapidly starting gas turbine power plants and load shedding).

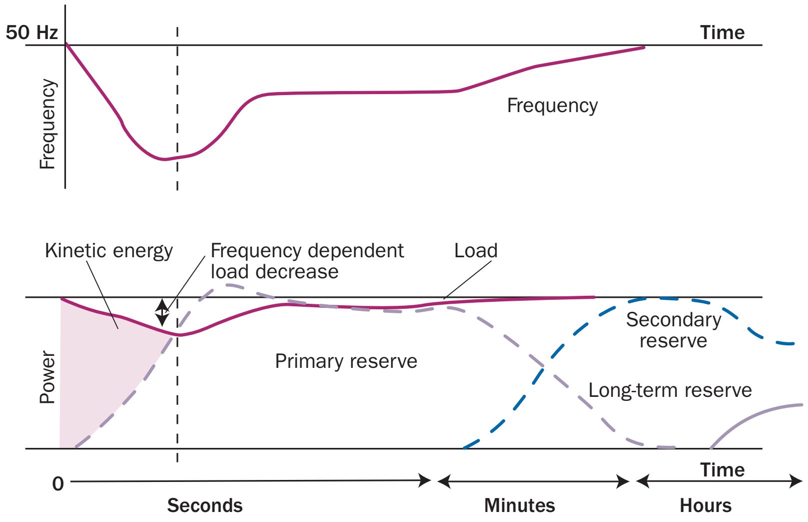
Because changes in loads and generation, resulting in a power imbalance, are not typically predicted or scheduled in advance, primary and secondary control operate continuously to keep system frequency close to its nominal value.

Consumption of electrical power varies per minute, hour and day. Because the power balance must be continuously maintained, generation is scheduled to match these longer term variations. Such economic dispatch decisions are made in response to anticipated trends in demand (while primary and secondary control continue to respond to unexpected imbalances). During the early morning period, for example, an increase in load usually occurs from approximately 7:00 AM to mid-day or early afternoon. After the daily peak is reached, the load typically falls over the next several hours, finally reaching a daily minimum late at night.

Some generators require several hours to be started and synchronized to the grid. That means that the generation available during the mid-day peak must have been started hours in advance, in anticipation of the peak. In many cases, the shut-down process is also lengthy, and units may require several hours of cooling prior to restarting. The decision to utilize this type of unit often involves a period of several days that the unit must run prior to shutting down in order to be economic. This time scale is called unit commitment, and it can range from several hours to several days, depending on specific generator characteristics and operational practice.

During the operational hour, the balancing task is usually taken over from the individual power producers by the system operator. This is cost-effective, as the deviations of individual producers and loads smooth out when aggregated, and only the net imbalances in the system area need to be balanced to control the frequency. System operators have the information on schedules for production, consumption and interconnector usage. These schedules either are made by themselves or are provided by electricity market or actors involved (producers, balance responsible players or programme responsible parties). They may also use on-line data and forecasts of for example load and wind power to assist them in their operational duty. During the operational hour they follow the power system operation and call producers that have generators or loads as reserves to activate them according to the need, to balance power system net imbalances.

Figure 16: Activation of power reserves and frequency of power system as a function of time when a large power plant is disconnected from the power system



Source: Holttinen, ref. 2

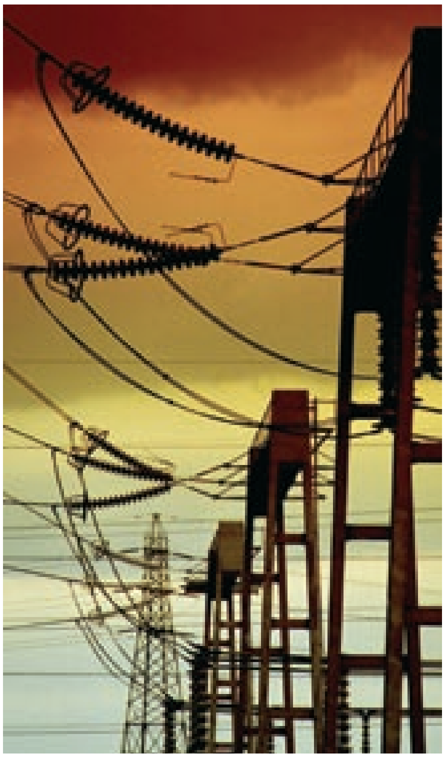


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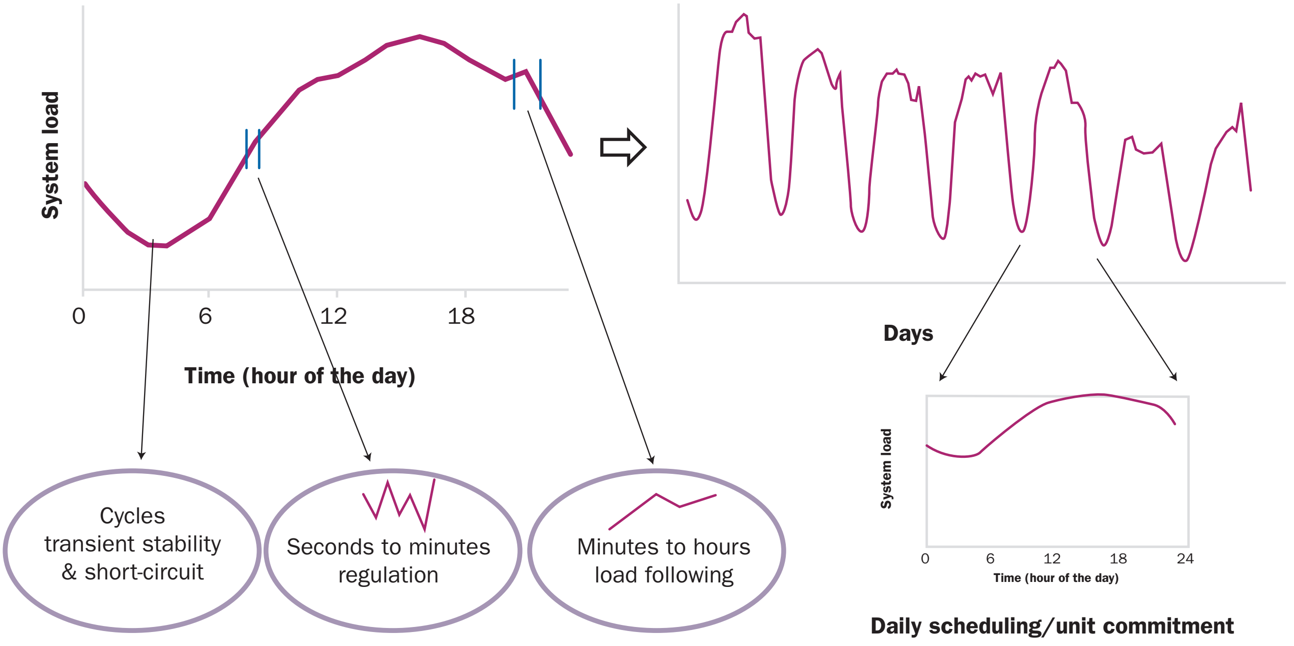
Figure 17: Time scales for utility operations



Source: Parsons ref. 59

4.2.1 Balancing demand, conventional generation and wind power

4.2.1.1 Effect on scheduling and operating of reserves

To balance the demand and supply, power plant generation is scheduled to match anticipated trends in demand. For any deviations from the anticipated trends, primary and secondary reserves are operated continuously to keep system frequency close to its nominal value (see box).

■ Primary and secondary reserves

Wind power may affect the use of primary and secondary reserves during the operational hour. However, as shown in par. 3.3, the time scale where relevant changes in large scale wind power occur is the secondary reserve (10 minutes…hour). Wind power development will have little to no influence on the amount of primary reserves needed, as concluded by several studies (Dany, ref. 67). On second/minute time scales fast variations in total wind power capacity output occur randomly, like the already existing load variations. When aggregated with load and generation variations, the increase due to wind is very small. Furthermore, the amount of primary reserve allocated in the power systems is dominated by outages of large thermal generation plant, hence more than large enough to cope with these very fast variations.

■ Secondary and tertiary reserves

To assess the impact of wind power on the secondary/tertiary reserves, the variability of large scale wind power during the hour during which the System Operator assumes control is relevant. Even in extreme cases, the output of distributed wind power plants does not change more than ± 10% of installed capacity in one hour in larger areas (four Nordic countries), or ± 25% of installed capacity in smaller areas (West Denmark storm case), as shown in Chapter 3. For the use of reserves, all variations that have been unpredicted will affect the net system imbalance. Some of the wind power production has been taken into account in scheduling the other generation units. Part of the wind power production will remain unpredicted. Aggregating wind power imbalances together with all other deviations from schedules (especially load forecast errors) will determine the total net imbalance and the reserves needed for the power system. In principle the power producers can try to correct their production levels to the scheduled levels up until the operating hour by trade or re-scheduling their own conventional capacity. If this was done, then only the in-hour variability of wind power would affect the secondary reserves. Studies made so far (see paragraph 4.2.2) show that only from penetrations levels of gross consumption of 10% onwards the impact of wind power on the secondary reserves will be significant and increase. The largest impact of wind power will be on how conventional units are scheduled to follow load (hour to day time-scales). During the morning load pickup more resources must be dispatched. If wind generation is also increasing and can be forecasted reliably, then fewer load following resources would be needed in the system. Conversely, wind output could drop during the morning load pickup. If a wind plant's output could be perfectly forecasted for 1-2 days in advance, it would help schedulers determine which units would need to be committed. In the absence of a perfect forecast, the unit-commitment decision has some uncertainty. 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 much wind power production is expected– the more flexible power units there are, the later the unit commitment decisions need to be done.

4.2.1.2 Short-term forecasts of wind in system operation

Short term forecasting is useful for all producers with wind power in their portfolio. It becomes more and more important also for system operators when wind power penetration increases. In addition, for very short time horizons (10 minutes…3 hours), on-line information of wind power production enables accurate predictions. The usefulness of the tools described in Chapter 3 is proven by existing practice. **In some European regions with a high level of penetration – regions in Spain, Germany and Denmark – operators are routinely forecasting output from their wind farms. These forecasts are used to schedule the operations of other plant, but are also used for trading purposes. Because of the zero fuel cost of wind power, it comes in early in the merit order. On a power market exchange, the effect is that power prices drop when the wind picks up.**

The benefits of the application of short-term forecasting depend highly on national regulatory-, technology- and site-specific issues. The parties acting in electricity markets benefit from wind power prediction tools (ref. 6) in different ways as shown in Table 9.

Table 9: Benefits of short-term forecasting for various stakeholders

ACTOR	BENEFITS
Energy supplier or balance responsible player	Improve supply and demand matching (through more/less purchase of peak generation capacity) Submit better estimates of electricity production to the system operator Reduce balancing charges to be paid to the TSO
Wind farm operator (without fixed price PPA)	Provide better information on expected power output to the energy supplier, resulting in higher receipts due to sharing of benefits in the field of balancing (see above)
Distribution System Operators	Improve network management through better information about expected power flows, thereby lowering network operational costs and reducing or possibly postponing grid investments
Transmission System Operators	Improve network management through better information about expected power flows, thereby lowering network operational costs and reducing or postponing network investments. If the TSO makes the forecast information public to the market, balancing the system will be easier and balancing costs for the total system will decrease

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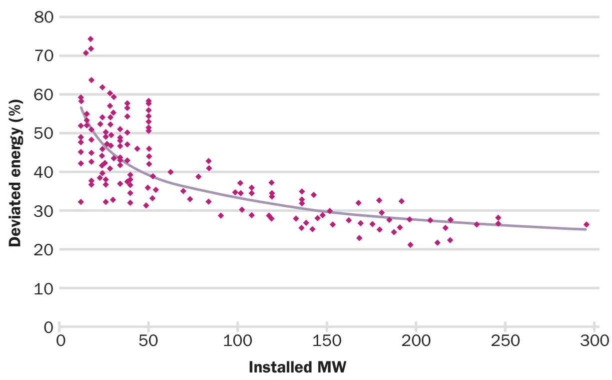
National circumstances strongly determine which party invests in a wind power prediction tool:

- In the UK, power producers are obliged under the New Electricity Trading Arrangements (NETA) to remain within the agreed power output. If a wind farm operator cannot stay within this band, penalties are charged. Therefore, it is in the interest of the operator to invest in a forecast tool.
- In Germany and Denmark the TSO/DSOs are solely responsible for the system balance and are obliged to connect any wind producer and purchase all RES electricity offered to them. Therefore, system operators are benefiting from investing in forecast tools in those countries.
- In the Netherlands, the electricity supplier (access responsible party) is usually the party bearing the responsibility for a sound energy program on behalf of small-scale wind power producers. The ARP will have to cover any imbalance costs and could therefore be motivated to invest in forecast tools
- In Spain, the forecast error used for calculating the balance penalty is expressed in terms of Mean Absolute Percentage Error, which is the relative deviation between forecasted and produced energy on an hourly basis[21]. The deviation of actual wind power production with respect to the scheduled production is paid according to the deviations of the whole system that is now of around 30% of the market price €9/MWh. For the regulated tariff, the balance penalty (cost of deviation) is fixed each year (in 2004 this was around €7/MWh). The balance penalty only applies for the amount higher or lower than 20% of the scheduled electricity. The beneficial effect of the size of the wind power portfolio on the accuracy of the forecast is illustrated in Figure 18.

Figure 18: Forecast accuracy in Spain as a function of the portfolio size. The aggregation of wind farms reduces the mean absolute percentage error (MAPE) from 40% to approximately 25% of deviated energy



Source: Wind2Market

- In California (USA), new wind farms are required to "use best possible means available" to forecast the output and send such estimates to the California ISO (ref. 58). Recently a new programme was formed: PIRP (Participating in Intermittent Resource Programme). The wind power producers pay a fee for forecasting to the system operator who makes the forecast for all wind power producers. The imbalance payments are settled according to monthly net imbalance, which means that the hourly imbalances of wind power cancel each other out for the most part.

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[21] $\text{MAPE} = \frac{\sum_h |e_h - c_h|}{\sum_h c_h} \cdot 100$

with e_h: Casandra energy production forecast for hour h
c_h: Real measured energy production in hour h

4.2.2 Required balancing capacities and balancing costs: overall results from system studies

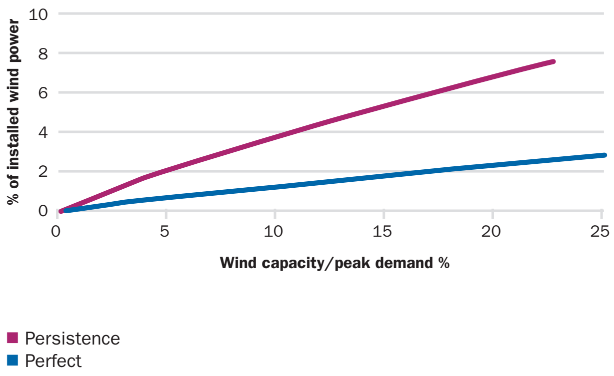
The integration of wind power into regional power systems has mainly been studied on a theoretical basis, as wind power penetration is still rather limited in most European regions. Even though the average annual wind power penetration in some island systems (e.g. Crete in Greece) or countries (e.g. Denmark) is already high, on average wind power generation represents only 1–2% of the total power generation in the Nordic power system (Nordel) or the Central European system (UCTE). The penetration levels in the USA (regional systems) are even lower. Driven by the fast growing wind turbine market, wind power impacts are to an increasing extent the subject of studies on country and regional level.

This paragraph intends to describe generalised findings of such studies, whereas a short description of the results of some important studies is given in paragraph 4.2.3. The results from studies made so far should be looked at with care. They all use different assumptions, do not always have sufficient data for wind power and load uncertainties nor assume the most cost effective options for balancing. The time horizon used for wind power forecasts in the power system operation is crucial as forecast accuracy determines the impacts – and there is a large variation in the assumed forecast horizon. Studies using uniform methodologies are needed.

On the time scale of seconds/minutes (primary control) the estimates for increased reserve requirements have resulted in a very small impact (ref. 67, Dany). This is – as discussed in paragraph 3.3.2 – due to the smoothing effect of very short term variations of wind power production; uncorrelated as they are, they cancel out each another, especially when mixing in with other fast variations of loads and generation units.

For the time scale of 15 min…1 hour (secondary control) increasing wind power penetration will increase the impact that wind power has on the net imbalances of the power system. The estimates for the extra reserve requirements due to wind power is in the order of 2…8% of the installed wind power capacity at 10% penetration of gross consumption (refs. 64, 69, 70). Here the results differ according to how many hours ahead wind power forecast errors are being corrected by reserves. Some studies use day-ahead forecasting and some studies only look at how much wind varies during the operational hour to determine the increase in reserve requirement. **When using good forecasting techniques and an intra-day scheduling system, the required additional reserves are in the range of 2-4% of installed wind power capacity at 10% (energy) penetration.**

Figure 19: Additional balancing power (capacity) for wind (expressed in percentage of installed wind power) as a function of wind power capacity penetration[22]. The amount of regulating power can be reduced by improved forecasting (based on Milligan, NREL, ref. 69). At 20% capacity penetration, 7% of wind power capacity is needed for balancing, if persistence is assumed. Assuming a perfect forecast, only 2% additional capacity would be needed at this penetration level. The values shown are relative and intend to illustrate the beneficial effect of forecasting on additionally required reserve capacity. The absolute values are very much region, system and market dependent.



Source: Milborrow, ref. 70

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[22] Assuming an average ratio of peak to average demand of 1.44 and an average wind power capacity factor of 25%, wind power capacity penetration is 2.8 times the wind 'energy' penetration. On the X-axis of Figure 19, 20% capacity penetration corresponds to approximately 7% energy penetration.

Both the allocation and the use of reserves imply additional costs. In most cases, the increase in reserve requirements can be handled by the existing conventional capacity. This means that only the increased use of dedicated reserves, or increased part-load plant requirement, will cause extra costs (energy part). The technical cost of operating for example fossil fuelled power plants in part load operation is 5—10 €/MWh and for hydro power it is less. The cost of reserves can be estimated with these prices as long as there is enough capacity to provide for the increased reserve need. If not, either more expensive options need to be taken for the special hour(s) or new options need to be developed (like demand-side management, storage or using wind farms). **The consensus from most studies made so far, is that the extra reserve requirements needed for larger wind power penetrations is already available from conventional power plants in the system, i.e. no new reserves would be required.**

Estimates of the extra cost of secondary load following reserves suggest €1–3/MWh for a wind power penetration of 10% of gross consumption (refs. 2, 67, 76, 160, 161)[23]. In California, the incremental regulation costs for existing wind power capacity is estimated to 0.1 €/MWh, for wind energy penetration of about 2% (Kirby et al, 2003). On-going research on this subject to be mentioned is a recently commenced study in grid integration through the International Energy Agency's IEA Wind Implementing Agreement[24].

Table 10: Balancing requirements and costs at different time scales

Type of reserve	Effect of wind power on the reserve requirement	Factors affecting the additional cost
Primary reserve (minute to minute or less)	Nil	Geographical dispersion
Secondary/Tertiary reserve (15 minutes, hour to hour)	Regulating capacity 2% of wind rated capacity at low penetrations and 4% at higher penetration levels Costs : €1-3/MWh wind at penetrations up to 10%, at higher penetrations : €3-4/MWh wind	Geographical dispersion, Forecasting
Load following (4-12 hours)	Efficiency loss due to wind power variations and prediction errors Reduced fuel use and reduced emissions. Wind is replacing the most costly power units, operating at the margin, by the forecasted amount of wind power production. The forecast errors will either come to the regulating/balancing power market, or be settled by producers when more accurate closer to delivery time forecasts appear	Prediction errors Correlation of wind power and load Production mix

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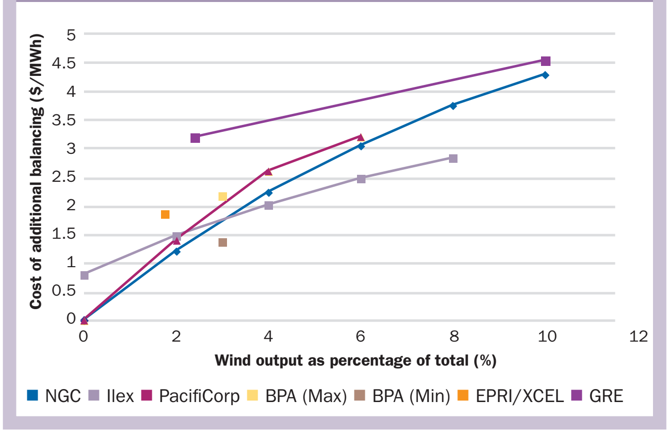
[23] Currency exchange rate from the end of 2003 used: 1 € = 1.263 $; 1 € = 0.705 £

[24] http://www.ieawind.org/

Figure 20: Estimates of additional balancing costs from six studies



Source: ref. 41

4.2.3 Details from country and region specific studies

■ Germany

The German example (DENA, ref. 89) illustrates that the required positive and negative regulation capacities can be met with the existing generation plant configuration. The required amount of wind-related regulation and reserve power directly depend on the quality of short term wind power prediction and the resulting deviation between predicted and actual values of wind power. In the Dena grid study, a further improvement of wind power prediction quality has been assumed. Wind power plant capacity and generation figures are given in Table 11. The total generating capacity in Germany is around 125 GW (2003), 40 GW of which have to be replaced before 2020.

To balance unforeseen variations in wind power, short-term and hourly reserves must be provided, capable of positive and negative regulation. In 2003, an average of 1,200 MW and a maximum of 2,000 MW of wind-related positive regulation power had to be available one day ahead in Germany. By 2015, that amount would rise to an average of 3,200 MW and a maximum of 7,000 MW. The mean value corresponds to 9% of the installed wind power capacity and the maximum to 19.4%. These capacities have to be available as positive minute and hourly reserves. In 2003, an average of 750 MW and a maximum of 1,900 MW of wind-related negative regulation power had to be available one day ahead. By 2015, that amount would rise to an average of 2,800 MW and a maximum of 5,500 MW. The mean value corresponds to about 8% of the installed wind power capacity, and the maximum to 15.3%.

The DENA study showed that wind energy in Germany can expand from almost 17 GW to 36 GW in 2015, causing annual wind power production to triple from 23.5 TWh in 2003 to 77.2 TWh in 2015, providing 14% of the German net electricity consumption in 2015. This can be achieved without any additional need to add reserve or balancing power stations.

The wind-related regulation and reserve capacities can be covered by the conventional power generators and its operating method as developed in this study. No additional power stations need to be installed or operated for this purpose.

An overview of the required balancing power capacities is given in Table 12. In 2015 on average 3.2 GW positive regulation power representing 9% of the installed wind energy capacity and 2.8 GW negative regulation power representing 8% of the installed wind energy capacity is required.

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Table 11: Characteristic numbers of wind power capacity and generation in 2003 and 2015 in the scenario of the Dena study

	2003	2015
Installed wind power capacity (GW)	14.5	36
Annual wind energy generation (TWh)	23.5	77.2
Effective capacity factor	18%	25%
Wind energy share of annual electricity demand	5.5%	12.5%

Table 12: Overview of required regulation power (day ahead reserve) in 2003 and 2015 as found in the Dena study. Installed wind power capacity 14.5 GW in 2003, and 36 GW in 2015. These capacities (primary and secondary reserves) have to be scheduled to cope with unforeseen changes in wind power output with respect to the schedules.

	2003		2015	
	average	max	average	max
Positive regulation capacity (MW)	1.2	2	3.2	7
% of wind power capacity	9	14	9	19
Negative regulation capacity (MW)	0.75	1.9	2.8	5.5
% of wind power capacity	5	14	8	15

It is not possible to derive the additional balancing costs directly from the information in the Dena report, because of the lack of transparency in the cost calculation methods used.

■ Nordic region

In a study by Holttinen (ref. 2) the increased reserve requirement due to integrating wind in the Nordic power system (Denmark, Sweden, Norway, Finland) is determined by simulation based on a 3-year time series, combining the wind power variations with varying electricity consumption. It was found that wind power, combined with the varying load, is not imposing major extra variations on the system until a substantial penetration is reached. The increased reserve requirement is seen on a 15 minutes to one hour time scale. In the Nordic countries wind power would increase the reserve requirements by 1%, 2% and 4% of wind power capacity at 5%, 10% and 20% penetration (energy basis) respectively. The increased reserve cost is of the order of €1/MWh at a 10% penetration level and €2/MWh at 20% penetration of wind power. The estimation is conservative, the values would be reduced by 50% if the costs of new reserve capacity were not allocated only to wind, and if only the increased use of reserves is taken into account.

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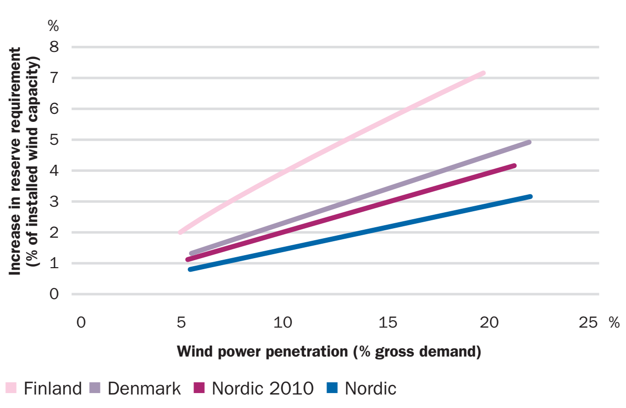
Figure 21: Additional system reserve requirements in the Nordic area (as percentage of installed wind power capacity) as a function of wind power (energy) penetration. The amount is determined for individual countries and for the whole area. The beneficial effect of geographical dispersion on required reserves is obvious.



Source: Holttinen, ref. 2

These results are significantly lower than, for example, the dena report results. This is mainly due to two things: first, the area of study is much larger covering the whole of the four Nordic countries. This illustrates the advantages of operating the Nordic power system as an integrated system co-ordinately. Secondly, the results are calculated from the variability during the operating hour, so forecast errors of wind power on longer timescales are not taken into account. The parties responsible for balancing in the Nordic power system have the opportunity to change their schedules up to the operating hour. This means that part of the prediction error could in principle be corrected when more accurate forecasts arrive.

■ Denmark

The study reported in ref. 63 and ref. 64 describes the model SIVAEL and its application on the Danish system. The model SIVAEM allows calculation of the required regulation power.

A case study for Denmark by Østergaard (ref. 19) analysed the Danish system with various level of wind power up to 80% penetration. At these levels of penetration, extensive active control is needed from all generators including small CHP. Heat pumps offer a valuable means for reducing demand and for controlling load (in combination with heat storage).

■ UK

In the UK, studies have been done on the subject by, e.g. Strbac (known as ILEX 2002, ref. 161) and by the National Grid Company (NGC, ref. 160).

With wind supplying 10% of the electricity demand, the required additional reserve capacity are in the range of 3% to 6% of the rated capacity of wind plant. With 20% wind, the range is approximately 4 to 8%.

According to NGC, accommodating 10% wind in the UK system would increase balancing costs by €3.9/MWh of wind and 20% wind would increase those costs by around €4.6/MWh of wind.

■ Ireland

In a report commissioned by Sustainable Energy Ireland SEI (ref. 76), the additional cost of reserves was estimated for different system operation strategies. The forecasting strategy resulted in lowest extra costs (€0.5/MWh for 10% wind energy penetration). This was estimated from few sample days of operation with 3 hour-ahead forecasts for scheduling the generation.

■ Spain

A national system study quantifying the impact on the system reserves and the additional balancing costs is not available. On the other hand, a lot of efforts are spent to keep the balancing costs low, by systematically using short-term forecasts. In addition, there are market players offering jointly cogeneration and wind on the balance market which minimises the deviations and reduces the need for balancing power.

Moreover in several regions and states in the USA, system studies have been carried out by utilities and system operators. An overview is given in ref. 59.

4.3 Operating power systems with wind power from the system operators viewpoint

Transmission level

A TSO's task of balancing and securing system operation involves the use of transmission lines in the system area and the interconnections to neighbouring systems. The issues include congestion management, priority access and priorities in curtailment in critical situations (low demand, high wind). Managing the power flows with congestion management is described in chapter 6.2.

High penetration levels of wind power production have implications for the planning and operation of the transmission system. Voltage control in the system (for example in the neighbourhood of large wind farms) may be required in order to cope with unwanted voltage changes (which might be enhanced by variable-output wind power). This voltage support could be supplied by the wind farm itself if adequate wind energy technology is used, otherwise dedicated equipment has to be installed, such as FACTS-devices[25].

Another issue is the management of power flows and possible congestions in the grid. Specific combinations – both in level and in geographical location - of wind power production and demand can cause changes in the magnitude and the direction of power flows in the transmission grid resulting in changing cross border flows. Also for this purpose, TSOs need high quality wind forecast tools. FACTS-devices, such as phase-shifting transformers, may also be used for the management of power flows.

Distribution level

Grid connection of wind power until now has very often been done at distribution level. A particular feature of distribution grids is that there is no active management such as on transmission level. The distribution grids have to cope with higher distributed generation levels, without reducing the quality of supply seen by other customers. **Certainly, 'embedded generation' of wind power adds advantages to the grid. Weak grids may be supported by wind power, and the users on the line may be better served, as wind power adds to the grid voltage. Power electronics of wind farms can improve power quality characteristics in the grid. The power – if consumed within the distribution network – gets directly to the user and transmission costs can be avoided. Finally wind power may keep parts of the system operational in the event of transmission failures which otherwise would cause black outs.** Adding wind power results in similar effects as in the transmission grid: changing of direction and quantity of real (active) and reactive power flows, which may interact with operation of grid control and protection equipment. The design and operation practices at the distribution level may need modification as more distributed generation such as wind power is added. Distribution grids may have to become more "actively managed". This requires the development of suitable equipment and design principles but the improved grid yields collateral benefits for the distribution grid operator.

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[25] FACT: Flexible AC Transmission System devices such as Static Var Compensators (SVC).

4.4 Options for increasing flexibility of the power system

The availability of balancing solutions (generation capabilities, load management, energy storage) in power systems is an important factor for the integration of wind power in power systems. More research is needed to investigate the technical capabilities and economic effects of various solutions. Even though power system balancing is not a new problem, wind power does provide a number of new challenges which will need to be addressed if the amount of wind power increases above certain levels.

4.4.1 Flexible generation

Existing balancing solutions involve mostly conventional generation units: hydro-power and pumped hydro, and thermal units. Hydro-power is commonly regarded as a very fast way of reducing power imbalance due to its fast ramp-up and ramp-down rates. On top of this, it has a marginal cost close to zero, making it a very competitive solution. Pumped-hydro furthermore allows energy storage, making it possible to buy cheap electricity during low-load hours and selling it when demand and prices are higher. Thermal units are commonly used for power system balancing as well (primary control, secondary control). Of these, gas fired units are often considered to be most flexible allowing a fast adjustment of production.

4.4.2 Storage options

Grid operators have to match supply to demand over a wide range of time periods (ref. 77). Each task may be associated with specific forms of generation, storage and load control. Table 13 summarizes the time characteristics required for storage applications.

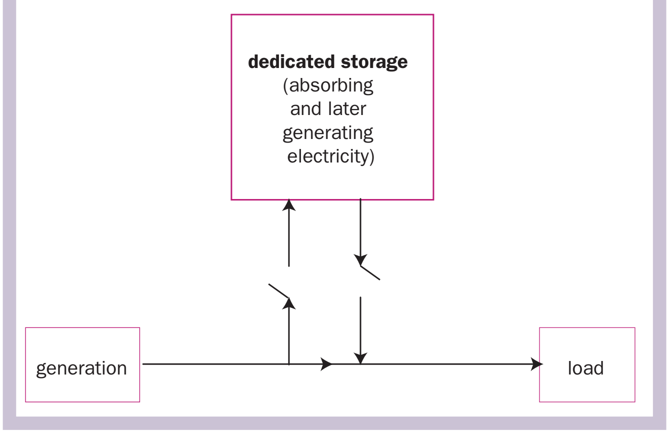
Table 13: Time characteristics required for storage applications

Task	Period
Output smoothing	Intermittent ~ second
Load-levelling	Daily 4-12 h Weekly 40-60 h Seasonal 3 month
Peak Shaving	180-10000 s
Spinning reserve	30-300 s
Voltage stabilisation, frequency regulation	0.5-120 s
Countermeasure against supply disruption	0.12-0.2 s
Improvement of stability	0.02-0.2 s

Source: ref.77

The range of technologies for dedicated-storage is potentially wide, however pumped-hydro power installation is the most common and best known technology. Other technologies include: compressed air, flywheels, batteries (lead acid, advanced), fuel cells (including regenerative fuel cells, 'redox systems'), electrolysis (e.g. hydrogen for powering engine-generators or fuel cells), 'super-capacitors'.

Figure 22: Basic principles of dedicated-storage



Source: Auer, ref. 77

The use of dedicated-storage normally results in overall loss of energy, i.e. the electrical energy absorbed is more than the electrical energy regenerated. The electricity in/electricity out efficiency of dedicated storage is commonly about 80%. There is increasing interest in both large scale dedicated storage effecting transmission networks, and in smaller scale dedicated storage embedded in distribution networks.

4.4.3 Demand-side management

With demand-side management, loads are influenced to respond to power imbalances by reducing or increasing power demand. Part of the demand can be time shifted (for example heating of houses or swimming pools or cooling/refrigerators) or simply either switched off/on according to price signals. This allows a new balance between generation and consumption, without having to adjust generation levels.

Demand-side management is much less commonly applied today than adjusting generation levels. The availability of this solution depends on load management possibilities (for example, steel mills) and the financial benefits flexible load contracts offer to the load (cost of power-cuts and power-increases versus lower bills).

4.4.4 Wind power cluster management

In the following paragraph it will be illustrated that by operating wind power plants as Virtual Power Plants (VPP, ref. 72), they can perform more tasks in the power system than just power production, in other words they can also provide ancillary services.

The pooling of several large (offshore) wind farms into clusters in the GW range will make new options feasible for an optimised integration of variable-output 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 optimised network management and optimised (conventional) generation scheduling. The clusters will be operated and controlled like large conventional power plants.

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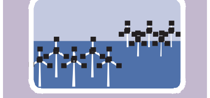
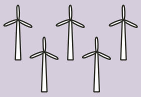
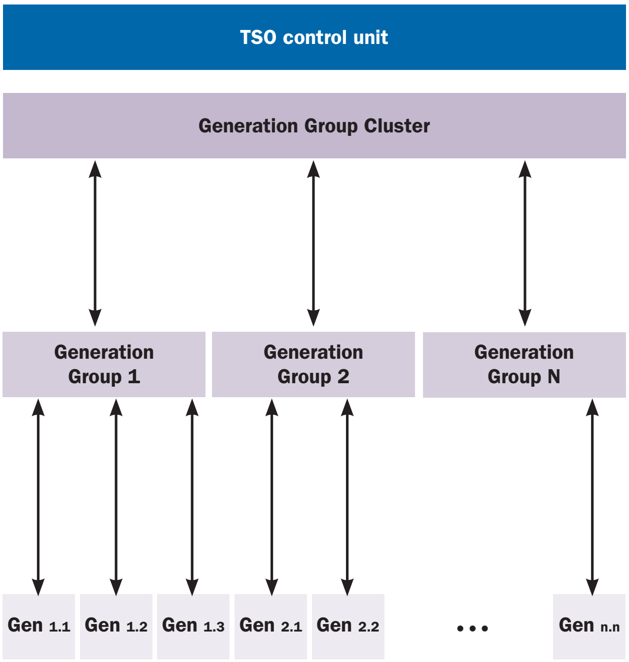
Figure 23: Wind farm cluster management system

Generation Group Cluster 	**Requirements:** **Profile Based Operation Mode** • uninfluenced operation • power limitation • energy compliance • constant power output • supply of control energy
Generation Group 	**Requirements:** • maximum power limitation (dynamic threshold values) • short circuit current • emergency cut-off (disconnection) by network outages • coordinated start-up and shut-down procedures (gradients limitation)
Single Generator 	**Requirements:** • safe and reliable operation • maximum energy yield



Source: ISET, 2005

Since 100% accuracy of wind power forecasting is not achievable, the difference between the forecast and actual supply must be minimised by means of control strategies of wind farm cluster management to ensure the generation schedule. Power output in this case will be controlled in accordance with the schedule determined by short-term forecasting. This strategy has a large impact on wind farms operation and requires matching of announced and actual generation on a minute-to-minute basis. The schedule execution should be achieved within a certain (determined by forecast error) tolerance band. Time-variable set points should be constantly generated and refreshed for an optimum interaction between wind farms and wind farm cluster management. A continually updated short-term forecasting for wind farms and cluster regions is assumed for this kind of operation management. The following control strategies will be worked out:

- limitation of power output;
- energy control;
- capacity control;
- minimisation of ramp rates.

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

Contribution of wind power in congestion management

From time to time wind power generation achieves and can exceed the maximum permissible thermal ratings 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 optimisation of the process.

Losses reduction, optimisation of active and reactive power flows

Wind power generation is variable not only in the time domain, but also geographical variations can lead to power flows over large distances with associated losses. Such situation 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 the economical value to the system of wind energy, by keeping the additional costs for balancing to a minimum level.

Based on innovative wind farm operational control, a control unit between system operators and wind farm clusters, Wind Farm Cluster Management will enable a profile based generation 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.

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4.5 Conclusions

The possibilities and detailed strategies for managing variable-output wind power vary between national and regional power systems (ref.57).

Like any other form of generation, wind power will have an impact on power system reserves. It will also contribute to a reduction in fuel usage and emissions. The impact of wind power depends mostly on the wind power penetration level, but it also depends on the power system size, generation capacity mix and load variations.

Large power systems can take advantage of the natural diversity of variable sources. **A large geographical spread of wind power will reduce variability, increase predictability and decrease the occurrences of near zero or peak output.** The power system has flexible mechanisms to follow the varying load that cannot always be accurately predicted. The uncertainty to be managed in system operation is driven by the combined effect of the fluctuations both (i) in demand, and (ii) in generation from conventional and renewable generation. These individual fluctuations are generally not correlated, which has an overall smoothing effect with a consequent beneficial impact on the cost.

On the second to minute time-scale wind power has very little if no impact on the reserves (primary reserve). This is because the large number of individual turbines will have their second-to-second variation uncorrelated and it will smooth out, together with the load variations.

On the 10 minute to hour time scale wind power will affect the reserves when the amount of wind power variations is comparable to load variations (secondary reserve). When **about 10% of total electricity consumption is produced by wind power, the increase in extra reserves is estimated to 2…4% of installed wind power capacity,** assuming proper use of forecasting techniques.

On time scale of hours to days, wind power will affect the scheduling of conventional power plants. On this time scale the impacts of wind power are dependent on forecast accuracy as well as how flexible the conventional power producers in the system area are.

Existing balancing solutions involve mostly conventional generation units. Other solutions for managing increased variability in the power systems include generation capabilities, load management, energy storage and using some of the wind power plants.

For a given geographical spread of wind farms good quality statistical forecasts can already be made and their accuracy is improving rapidly. Wind energy is thus variable but predictable. For the purposes of balancing these qualities, wind energy must be analysed in a directly comparable way to that adopted for conventional plant, which is not variable but is intermittent since large generating sets can be and are lost in an entirely unpredictable manner.

5 Grid connection requirements for wind power technology

5.1 General

Early wind power plant in Europe was connected to distribution networks, but, in recent years, more and larger wind farms have been connected to transmission networks. Each of these network levels has specific requirements when connecting wind power. The connection issues for the network are related to grid stability which is influenced by power flows and wind farm behaviour in case of network faults. At high wind power penetration levels, the grid support that wind power plants can deliver becomes important, assuming that transmission capacity is sufficient. Advanced simulation tools have been developed in recent years to investigate network stability in critical conditions, thereby simulating the behaviour of wind power plants with their specific control properties.

At distribution level, with the advent of renewable energy technologies and CHP, the amount of distributed (embedded) generation is growing rapidly. Distribution networks are less robust than transmission networks and their reliability – because of their radial configuration – decreases as voltage level decreases. Moreover, there is very little so-called "active" management of distribution networks. Rather, they are designed and configured on the basis of extreme combinations of load and ambient temperatures, (which reduce the capacity of overhead lines). Embedding generation – such as wind power – brings several system operation and economic advantages that are rarely recognised. In many situations network losses are reduced, because the generation is closer to the demand centres. Wind power also contributes to the reinforcement of the distribution grid and helps to maintain proper quality of supply which avoids additional investments. The addition of wind power to these networks creates new loading situations, changed power flow directions etc. which affect operation of network control and protection equipment, and necessitate modification of design and operational practices.

Grid operators (transmission, distribution) develop rules (grid codes) for connecting generators. Their grid codes have been complemented by specific codes for wind power plants, and the wind turbine manufacturers have responded to these requirements by design measures, mainly in the area of wind turbine control and electrical system design.

The subject of grid stability in view of increasing connection of wind power is discussed in paragraph 5.2. Grid connection requirements for wind power plants in various EU countries are described in paragraph 5.3. Advanced technical solutions for connecting very large wind farms to the network are presented in paragraph 5.4.

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5.2 Wind power and grid stability

The dynamics of power systems are mainly determined by the generators in the system[26], therefore it is important that the dynamic interactions between wind power plants and the electrical grid are well understood by grid operators, wind farm operators and the technology suppliers (wind turbine manufacturers). The issue can be looked at from two sides:

- How do wind farms and wind turbines respond to events and faults in the grid (sudden voltage drops etc. caused by transmission or generation faults)?
- How do wind farms affect the stability of the power system, what can go wrong, what are the implications on the transient stability of the network, voltage stability, frequency stability, critical fault clearance times etc.?

Dynamic system studies

In dynamic system studies, models are used to simulate the effect on the main system components of, for example, transient events and disturbances in the grid. Dynamic studies also indicate what kind of measures should be taken in the grid, and at the generators side when stability is threatened. Such studies are also carried out – in conjunction with steady-state load flow calculations - to investigate the amount of wind power that can be safely introduced in a power system before serious stability issues arise or measures become necessary to apply. The latter approach was followed in a recent study in Spain (see further in this paragraph).

The effect of wind power on the stability of power systems is the subject of a large number of studies. Just as for conventional technologies, such studies use advanced simulations tools to calculate the dynamic effects based on detailed characteristics of the power system configuration and of the generation plants (wind turbines). The challenge in this case is the fact that the type of electrical conversion systems in wind turbines (for example induction machines) is 'new' and has dynamical characteristics quite different from the classical generating technologies, with their synchronous generators.

Therefore, in order to study the effect, new advanced models have been developed to model the effect of various types of electrical systems used in wind turbines. For the purpose of dynamic simulations, wind farm models have been developed (e.g. refs. 90, 93) for the relevant wind turbine types (fixed speed and variable speed). Research on dynamic modelling of wind turbines is also undertaken under IEA (ref. 92). It is obvious that such models concentrate on the state-of-the-art electrical concepts for wind turbines (see the four types of systems described in par 3.2.1.1). Specific analysis tools have been developed for wind turbine electrical systems and control that are actually utilised. Because of the variety among and within the wind turbine types, specific simulation models representing the different wind turbine technologies and controls should be used. Examples are the model for synchronous generators, (ref. 85), and models specifically developed for DFIG systems, such as described in refs. 86 and 87.

Besides, dynamic system studies provide more insight on the ability of a wind farm to provide 'grid support' (ref. 79). Grid support, also termed 'ancillary services', represents a number of services that the power system operator requires from power generators, in order to secure a safe, reliable, stable and economically manageable grid operation.

These 'ancillary services' include support for e.g. (fast) output power or frequency control, voltage control and black start capability.

In general, from these dynamic studies it is concluded

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[26] Slootweg and Kling in ref. 1 page 650

that power systems dynamics are not a principal obstacle to increasing the penetration of wind power, provided adequate measures are taken. It is found that the modelling does not need to be overly detailed (ref. 60). For utility scale studies, aggregate wind farm models perform just as well as detailed models.

In particular, the technical measures required for wind power plants, formulated in the grid codes, are based on the results of these dynamic studies. Besides basic technical requirements for the wind farms, the codes require voltage support by fast reactive power compensation, which sometimes involves installation of additional equipment in the grid, close to the wind farm.

■ Capability of present methods

It should be remarked though that, in spite of the research efforts done in this area, some aspects of dynamic interaction of system and wind power plants require further clarification. Also, continued work is needed to improve the dynamic models for the latest wind turbine types and for entire wind farms. Such modelling efforts are becoming increasingly important because some TSOs are requiring wind farm developers to submit a dynamic simulation model of the wind farm before granting connection permits, in order to carry out dynamic grid integration assessment. This is a clear sign of the industry “coming of age”.

Some examples and conclusions of large dynamic studies are listed here:

- **Denmark:** a study undertaken by Eltra (ref. 88) on transient voltage stability in a system with a large amount of local (decentralised, connected to distribution network) wind power. The amount of wind power capacity connected to distribution networks is about 80% of the total wind power capacity in Denmark. Most of the ‘local’ wind farms are of older technology and just trip when registering grid abnormalities, hence the study recommended measures to compensate for restoring voltage, preventing overvoltage and incorporation of additional power reserves. Furthermore it was found that the installation of several smaller dynamic compensation units (reactive and inductive) in selected grid nodes yields the best results for voltage recovery.

- **Germany** (ref.89): A substantial part of the Dena study has been devoted to the network stability issue. It was concluded that there are no technical obstacles for wind power development to a penetration level of at least 15% (for the year 2015) if wind turbines comply with advanced grid codes particularly fault-ride through capabilities. Due to the uncertainty of the wind development scenario at higher penetration levels (for 2020) and its implication on the network stability, additional analyses of the wind power integration in the year 2020 are supposed to be done in a follow-up study.

- **Spain** (ref.91): a recent system stability study has been carried out jointly by the TSO (REE) and the industry organisation AEE for the joint Spanish and Portuguese system. The study looked at the maximum wind power capacity that the system can integrate at moments of peak load without exceeding the system limits. More specifically it investigated two scenarios, i.e. inter peak 65.4 GW, with a total wind production in the Iberian system of 16.75 GW, a summer ‘valley’ of 26 GW and a wind contribution of 6.45 GW. The goal in both cases was to demonstrate the safety of the system without going beyond the UCTE limits (loss of all kind of generation in a node which should not exceed 3.0 GW). The grid was modelled by REE who incorporated the models supplied by wind turbine manufacturers fulfilling the FRT rules as defined in PO 12.2. As expected, the results are quite dependent on the percentage of wind technology equipped with fault ride through capability. The admissible wind power capacity ranges from 13 GW to 20 GW. Some system behaviour characteristics at the high end of the installed capacity need to be further investigated such as low frequency oscillations, diminished short circuit power and voltage variations.

5.3 Connection and operational requirements (grid codes)

5.3.1 General

Based on system studies as described in paragraph 5.2, several TSOs have developed or are developing a set of specific requirements especially for wind farms. The aim of the requirements is to ensure that wind farms do not adversely affect the power system operation with respect to security of supply, reliability and power quality.

The generation technologies used in wind power are rather new for network operators (e.g. DFIG). The growth of wind power in a few European regions also has been faster than expected. As a consequence, the interconnection rules for wind farms are steadily being reformulated in the past years in parallel with the increasing penetration and wind energy technology development.

The rules are set by the electric 'bodies' (mainly TSOs) and not by governmental organisations. Harmonisation is being done on national level. The grid codes are often a source of controversies between network operators and wind farm operators. In general it can be said that wind turbine technology adapts to the codes. The variation in the technology of the existing wind turbine population reflects the history of the grid codes.

Grid codes and other technical requirements should reflect the true technical needs and be developed in cooperation between TSOs, the wind energy sector and truly government bodies. Often grid codes contain very costly and challenging requirements that have no technical justification. They are often developed by vertically-integrated power companies, i.e. within companies in competition with wind farm operators, in highly non-transparent manners. Furthermore, there are continuous changes of grid codes, technical requirements and related regulation, often introduced on very short notice and with minimum involvement of the wind power sector.

5.3.2 Overview of requirements

An overview of the aspects dealt with in the different codes is given in Table 14. For further reading, we refer to review of grid code requirements in refs. 1 and 96.

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Table 14: Essential requirements in national grid codes for wind turbines

Active power control	Several grid codes require active wind farm power control in order to ensure a stable frequency in the system and to prevent overloading of lines, etc. Grid codes are quite different in the extent of power regulation required.
Frequency control	Retention of the frequency in a power system within acceptable limits to ensure the security of supply, prevent the overloading of electric equipment, and fulfil the power quality standards.
Frequency range and voltage range	The requirement to be able to continue to operate even when the system is in difficulty, i.e. when voltage or frequency are far from the nominal values.
Voltage control	This implies requirements for reactive power compensation.
Voltage quality (rapid changes, flicker, harmonics)	A whole set of different requirements is included in national codes.
Tap-changing transformers	Some grid codes (E.on Netz, ESBNG) require that wind farms are equipped with tap-changing grid transformer in order to be able to vary the voltage ratio between the wind farm and the grid in case of need.
Wind farm protection	This category of requirements is intended to cater for situations with occurrence of faults and disturbances in the network. A relay protection system should be present to act for example in cases of high short-circuit currents, undervoltages, overvoltages during and after a fault. This should ensure that the wind farm complies with requirements for normal network operation and supports the network during and after a fault. It should equally secure the wind farms against damage from impacts originating from faults in the network. The so-called fault ride through (FRT) requirements fall under this category.
Wind farm modelling and verification	Some codes require wind farm owners/developers to provide models and system data, to enable the operator to investigate by simulations the interaction between the wind farm and the power system. They also require installation of monitoring equipment to verify the actual behaviour of the farm during faults, and to check the model.
Communications and external control	Unlike the requirements above, national codes are quite unanimous on this point. The wind farm operator should provide signals corresponding to a number of parameters important for the system operator to enable proper operation of the power system (typically voltage, active and reactive power, operating status, wind speed and direction etc.). Moreover it must be possible to connect and disconnect the wind turbines externally (only Denmark and E.on).

5.3.3 More details on essential grid code requirements

Essential grid code requirements are related to frequency, voltage and wind turbine behaviour in case of grid faults.

■ Frequency control

Several grid codes require the participation of wind farms in primary and secondary control, just like normal power stations do. This is not always obvious, as for example being capable of pushing the grid frequency up (= providing control at under frequencies) with a wind power station at all times in case of need is only possible when the wind farm is operated somewhat below its normal capacity. The requirement of frequency control includes frequency response capability, limitation of ramp rates and active power output.

- **Frequency response** – active power output: Frequency response is the capability to vary active power output in response to changes in system frequency. The capability is now required by the UK TSO only, but it could be expected that at high penetrations other TSOs will demand it, especially for “low demand – high wind” situations, when there may be few thermal sets with governors to provide frequency response. Wind farm operators may wish to consider the possibility of purchasing their frequency control obligation from another generator.

- **Ramp rates limitation:** Some TSOs require the limitation of positive and even negative changes of active power output (ramp rates) to suppress large frequency fluctuations caused by extreme wind variations and during wind farms start up and shut down. These requirements are expected to become stricter at higher wind penetrations in order not to exceed power gradients of conventional power plants responsible for primary and secondary control. The ability of wind farms to control their ramp rates will facilitate higher wind penetration: slightly sloping gradients ease wind power integration, steeper ones may be required in order to provide faster frequency. Currently the following ramp rates are requested:


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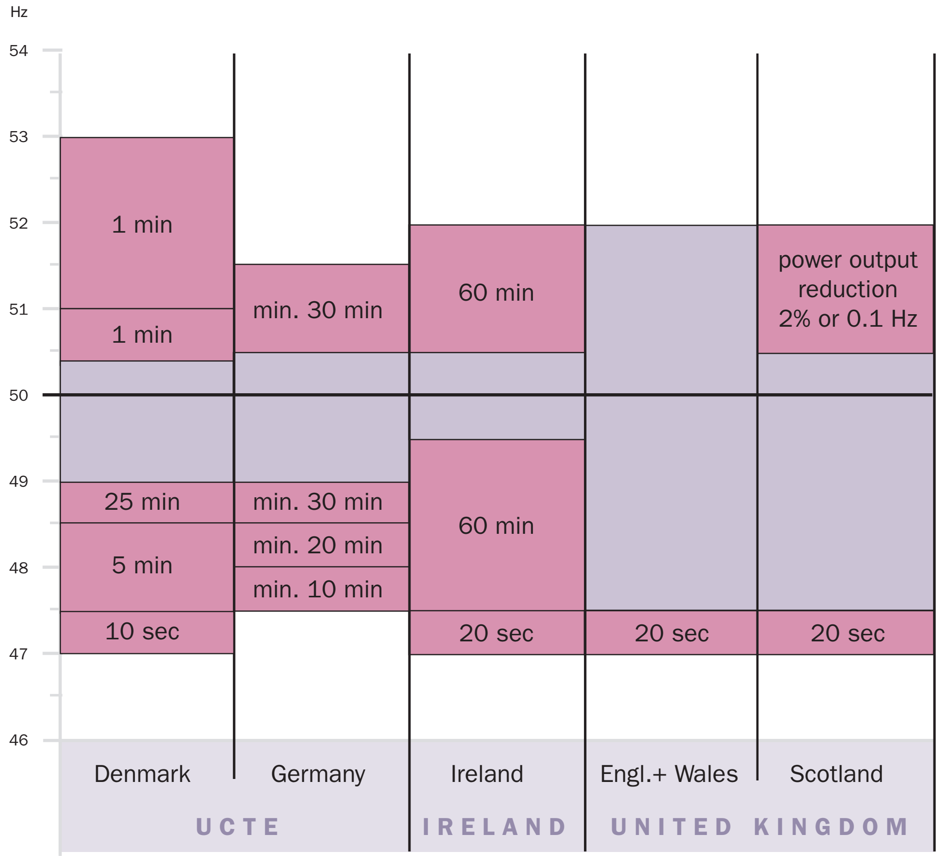
Table 15: Overview of required ramp rates in different grid codes

Positive ramp rates	Negative ramp rates (for wind farm shut down)
10% of rated power per minute in Germany,	Not specified
1-10 MW per minute (depending on wind farm capacity) in Scotland	3.3% of power output per minute in Scotland
1-30 MW per minute (specified by TSO) in Ireland (ESB)	Not specified

■ Frequency range

The nominal frequency is the same throughout a synchronously-operated system and is normally maintained within a narrow band. Any deviation from the planned production or consumption moves the frequency away from its nominal value. If the deviation is large enough, the frequency falls out of its normal range jeopardising the reliability of the power system. Abnormal frequencies increase the operating temperatures of generator windings, shorten the lifetime of insulation, and can damage power electronics. Previously, grid operators required wind turbines to disconnect from the network in the case of frequency drop. However, if increasing amounts of wind generation capacity disconnect at low frequency, this may affect the system's ability to recover. To ensure a secure power system operation in normal conditions and avoid problems during frequency restoration, some network operators have reversed their requirements and now require wind turbines to stay connected and operate at a wider frequency band. The requirements' summary is presented in Figure 24. Areas marked in blue depict frequency ranges where wind turbines should be able to operate continuously at full power output. Red frequency ranges require (time, power output or both) the limited operation of wind turbines, where they should stay connected to contribute to frequency restoration and stable power system operation. The synchronous zones of the UK and Ireland being smaller and having less inertia to prevent large frequency changes, they operate in a broader range than that of the European interconnected system.

Figure 24: Requirements for frequency range in which power production units should stay on-line



Source: A. Badelin ISET, 2005

■ Voltage control

The basic requirement of grid codes is the obligation for wind turbines to operate continuously at normal rated output in normal voltages ranges, maintain terminal voltage constant, and stay connected during voltage step changes within the voltage ranges specified. Other requirements include reactive power capability and voltage control. As wind is displacing conventional generation, wind turbines should be capable of supplying a proportion of the system reactive capacity, including the dynamic capability and contribute to the maintenance of the reactive power balance. Requirements of the grid codes for reactive power capability range from 0.925 (leading) to 0.85 (lagging).

Grid codes require that individual wind turbines control their own terminal voltage to a constant value by means of an automatic voltage regulator. This regulator protects the generator from supplying or absorbing too much reactive power by over and under excitation protection, which is especially important in dealing with transmission system voltage fluctuations. A modern wind farm is capable of controlling the voltage at the point of connection to a pre-defined set-point of grid voltage, as despatched from the TSO. Studies like ref. 83 show advantages for the system operator if wind turbines have expanded MVAr capabilities, because it offers the possibility of better balancing the reactive demand of the grid or parts of it.

■ Fault ride-through requirements

A particular concern of some TSOs is the ability of generators to remain stable and connected to the network when faults occur on the transmission network. This is known as fault ride-through capability (FRT) or low-voltage-ride-through capability. This contrasts with the TSOs requirements, just a few years back, when all wind turbines were required to disconnect during faults. 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 – in general – expected to trip only if a permanent fault occurs on the circuit to which they are directly connected[27]. Other generators that are connected to adjacent healthy circuits should remain connected and stable after the faulty circuits are disconnected. Every system is designed and operated to withstand a maximum sudden loss of a defined amount of generation capacity.

However, if generation connected to healthy circuits does not remain connected and stable during and after the fault, this 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 with the consequent danger of the system frequency dropping too rapidly and load shedding becoming necessary.

Fault ride-through requirements are specified in a few regions with large numbers of wind turbines. The detailed requirements of voltage level and duration of the fault often differ from country to country.

Grid codes and grid access requirements, including fault ride through requirements, should take into account that, at low penetration levels, excessive requirements such as fault-ride-through capability and voltage control possibilities are often required, but are not technically justified. Costly requirements should be included only if they are technically required for reliable and stable power system operation. The assessment of the need for requirements should be made by government bodies or TSOs that are fully separated from any generation activities, to avoid biased decisions.

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[27] The actual fulfilment of the FRT requirement is not always the case with large conventional generators such as for example some new CCGTs in Europe and nuclear power plants in USA.

5.3.4 Power quality

Power quality is a concept used to characterise an essential set of parameters 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 that are more susceptible to voltage fluctuations at 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.

Substantial work has been done in the development of a proper standard for characterising the power quality of wind turbines and for the measurement of the related quantities: IEC 61400-21 (ref.113) .

The application of the practices in this standard enables a careful evaluation of the impact of wind farms on the voltage quality in distribution networks. Instead of applying simplified rules which would be prohibitive for wind power, analysis with help of IEC 61400-21 methods is recommended (Tande in ref. 1 p.79) to carry out the following:

- Load flow analysis to assess whether slow voltage variations remain within acceptable limits;
- Maximum flicker emission measurements and comparison with applicable limits;
- Assessment of possible voltage dips due to wind turbine start-up;
- Estimation of maximum harmonic current and comparison with applicable limits.

IEC 61400-21 is currently undergoing revision aiming to include procedures for testing and characterizing power control and fault ride through capabilities of modern wind turbines.

5.3.5 National documents

Details of the existing codes for connection of wind power to transmission and distribution networks are given in Table 16 and Table 17.

Comprehensive overviews and discussions of national codes are also given (Refs. 1 and 96).

One view of the wind industry on the variety of the codes is voiced by S. Bolik (Vestas Wind Systems, ref. 96) :

"It exists a lot of different grid codes … all wind turbine producers have a product range which should be able to fulfil as many grid requirements as possible. … wind turbines will be designed for the codes for the biggest markets and the outer limits (highest requirements, red.) This is an obstacle for cost reduction of wind technology. Therefore a close working relationship between grid operators, customers and wind turbine producers is required to find acceptable demands in the near future."

This statement expresses well the need for collaboration to maximise wind energy's contribution and to integrate it with a minimum of unnecessary difficulty.

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Table 16 : Codes for connection to transmission level

Country	Document ref.	Title	Reference, year	Scope
Austria	TOR	Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen	E-Control 2004	Grid code for transmission & distribution
Belgium	Royal Decree 19/12/2002	Koninklijk besluit houdende een technisch reglement voor het beheer van het transmissienet van elektriciteit en de toegang ertoe	Staatsblad, 2002	Transmission Code
	ELIA internal doc.	Voorschriften en uit te wisselen informatie voor de aansluiting van productie-eenheden (Draft)	ELIA, 2004	Wind connected to transmission level
Denmark	TF 3.2.5	Wind turbines connected to grids with voltages above 100 kV	Energinet, 2005 (Eltra & Elkraft)	Wind connected to transmission level
Finland	-	No specific grid code available	-	-
France		Référentiel technique de RTE	RTE 2005	Transmission Code
Germany	Transmission Code 2003	Netz- und Systemregeln der deutschen Übertragungsnetzbetreiber	VDN, 2003	Transmission Code
	VDN Richtlinie	EEG Erzeugungsanlagen am Hoch- und Höchstspannungsnetz	VDN, 2004	Connection of renewable energy auto-production to the high-voltage level
Greece	Transmission Code, 30/5/2001	Transmission System Operation Code	HTSO	Transmission Code
Ireland	Grid Code	Grid Code, Version 1.1	ESB National Grid, 2002	Transmission Code
	WFPS1	Wind farm power station grid code provisions	ESB National Grid, 2004	Wind connected to transmission level
Italy	CEI 11-32	Impianti di produzione di energia elettrica connessi a sistemi di III categoria	Comitato Elettrotecnico Italiano	Connection of generators to HV (transmission level)
Netherlands	Grid Code	Netcode	DTE 2005	Grid code for transmission & distribution
Norway	guideline for wind farms >10MW (in preparation assisted by SINTEF)	guideline for wind farms >10MW (available on www.statnett.no from fall 2005	Stattnet	Connection of wind turbines
Poland		Instruction of Transmission System Operation and Maintenance		
Portugal		Regulamento do Acesso às Redes e às Interligações.	Entidade Reguladora do Sector Eléctrico (ERSE), 2001	Grid code for access to transmission & distribution
Spain	P.O. 12.1 P.O. 12.2	P.O. 12.1 Solicitudes de acceso para la conexión de nuevas instalaciones a la red de transporte P.O. 12.2 Instalaciones conectadas a la red de transporte: requisitos mínimos de diseño, equipamiento, funcionamiento y seguridad y puesta en servicio	MITYC	Grid code for transmission
Sweden	SvK	Affärsverket Svenska Kraftnäts föreskrifter om driftsäkkerhetsteknisk utformning av produktionsanläggningar	Svenska Kraftnät 2002	Decentralized generation connected to transmission level
UK	Engineering Recommendation G75/1	Recommendations for the connection of embedded generating plant to Public distribution systems above 20kV or with outputs over 5MW	Electricity Networks Association 2002	Embedded generation (large systems)

Table 17: Codes for connection to distribution level

Country	Document	Title	Organisation	Scope
Austria	TOR	Technische und organisatorische Regeln für Betreiber und Benutzer von Netzen	E-Control 2004	Grid code for transmission & distribution
Belgium	Lastenboek C10/11	Technische aansluitingsvoorschriften voor gedecentraliseerde productie-installaties die in parallel werken met het distributienet	BFE 2004	Decentralized Generation connected to distribution level
Denmark	TF 3.2.6	Wind turbines connected to grids with voltages below 100 kV	Energined 2004 (Eltra & Elkraft)	Wind connected to distribution level
Finland	-	No specific grid code available	-	-
France		Le référentiel technique	EDF Reseau Distribution	Distribution Code
	Arrêté du 17 mars 2003	Arrêté du 17 mars 2003 relatif aux prescriptions techniques de conception et de fonctionnement pour le raccordement à un réseau public de distribution d'une installation de production d'énergie électrique	Journal officiel de la République Française	Grid connection of production units to distribution level
Germany	Distribution Code 2003	Regeln für den Zugang zu Verteilungsnetzen	VDN 2003	Code for connection to distribution level
	Technische Richtlinie	Parallelbetrieb von Eigenerzeugungsanlagen mit dem Mittelspannungsnetz des EVU	VDEW 1999	Connection of distributed generation to the medium voltage level
Greece	Distribution Directive 129	Interconnection of power stations to the distribution grid	PPC	Connection of distributed generation to the low and medium voltage level
Italy	CEI 11-20	Impianti di produzione di energia elettrica e gruppi di continuità collegati a reti di I e II categoria	Comitato Elettrotecnico Italiano	Connection of generators to LV and MV (distribution level)
Netherlands	Grid Code	Netcode	DTE 2005	Grid code for transmission & distribution
Norway	TR A5329 / EBL-K 17-2001	Retningslinjer for nettilkobling av vindkraftverk	J.O. Tande, Sintef 2001	Connection of wind turbines
Poland		Instruction of Transmission System Operation and Maintenance		
Portugal		Regulamento do Acesso às Redes e às Interligações	Entidade Reguladora do Sector Eléctrico (ERSE), 2001	Grid code for access to transmission & distribution
Spain	RD 436/2004 OM 5/9/1985	Real Decreto 436/2004, de 12 de marzo, por el que se establece la metodología para la actualización y sistematización del régimen jurídico y económico de la actividad de producción de energía eléctrica en régimen especial	MITYC	Grid code for distribution
Sweden	AMP	Anslutning av mindre produktionsanläggningar till elnätet	Svensk Energi 2001	Code for connection to distribution level
UK	Engineering Recommendation G59/1	Recommendations for the connection of embedded generating plant to the Public Electricity Suppliers distribution systems	Electricity Networks Association 1991	Embedded (distributed) generation, small systems
	Engineering Recommendation G75/1	Recommendations for t he connection of embedded generating plant to Public distribution systems above 20kV or with outputs over 5MW	Electricity Networks Association 2002	Embedded generation (large systems)

The above regulations do not include network stability problems associated with high penetration levels of wind power.

5.3.6 Compliance with grid code requirements

Different wind turbine concepts comply with the grid codes requirements in different ways. Power plants consisting of wind turbines manufactured before the strict connection requirements came into force in some countries (around the year 2003) will require additional devices to become fully compliant. New wind turbines apply the latest technology, and are in principle designed to fulfil the connection regulations and contribute to system operation.

■ Frequency operating range

Early wind turbines (Type A) are generally not capable of meeting wider operational frequency ranges as stipulated in several grid codes. However, operation of a wind turbine in a wider frequency range is not really a complicated task as it mainly involves thermal overloading of equipment, in particular power electronic components, which have short thermal time-constants. A possible solution for short-term overload capability consists of over-sizing the converters, which in general can be done at reasonable cost. Another consequence of increased operating temperature is 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 ranges of frequency.

■ Frequency control (contribution to primary regulation)

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

The ability of generators to increase power output in order to support system frequency during an unexpected demand escalation or after a loss of a network element is important for system operation. 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.

The problem associated with network assistance by wind turbines is a reduced output and hence loss of income, which might not be offset by the rewarding of the primary control service. Furthermore, it is not the cheapest option for the system to have wind power contributing to primary regulation (loss of electricity produced at zero fuel costs), and should only be applied when other more cost effective options have been exhausted.

Moreover, since only recent wind turbine technology is capable to vary frequency response, the grid code requirement of participation in primary and secondary reserve is not suitable as a general provision in the grid codes. Such a requirement could also be in conflict with priority dispatching, attributed to non-programmable renewable energy sources.

■ Reactive power and voltage control

The capability of a wind turbine to control voltage and reactive power depends on its generator type. A squirrel cage induction generator applied in fixed speed wind turbines (type A) is a consumer of reactive power and needs additional equipment to provide fast control of reactive power (i.e. Static Var Compensators – SVCs or STATCOMs). This can be implemented as centralised compensation equipment of the wind farm or by individual wind turbines. Modern MW size wind turbines of Type A are mostly equipped with these devices, but the older machines of Type A would need modification in order to be able to provide reactive power control.

A doubly-fed induction generator (Type C) is capable of reactive power control, fulfils the requirement of the leading power factor of 0.925 without difficulties, but may have problems with the maximum power output when the lagging power factor of 0.85 is required. Compliance with this requirement demands increased frequency converter rating and possibly increased ratings of rotor and stator conductors.

■ Fault-ride through (FRT)

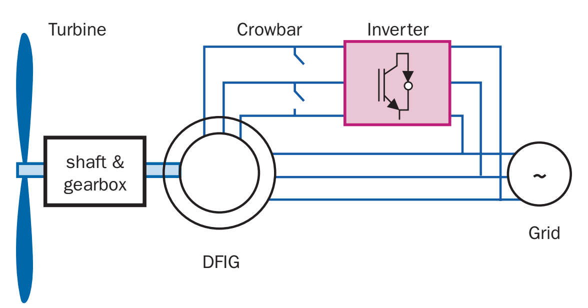
The capability of wind farms to support the grid in case of voltage dips in the system is an area that is still under development This paragraph outlines some general technical principles for the various wind turbine types.

The electrical system of Type A wind turbines is automatically disconnected from the grid in case of large voltage dips. Older systems of Type A do not have fault-ride through capabilities. Advanced wind turbines of Type A can be equipped with a UPS system[28], which enables them to provide local grid support in the case of outages.

Fault ride through with turbines of Type C is also possible. The technical method is often based on the so-called crowbar protection. During severe voltage dips due to grid faults, the rotor side power electronic converter is quickly disconnected from the grid in order to protect it against possible large current peaks during such events. In order to achieve this, the three-phase rotor winding is short-circuited via the so-called crowbar switch and consequently the DFIG generator behaves like a normal SCIG generator. The crowbar is released in a short time usually before the fault clearance. The units have thus the capability to provide reactive power support to the system during sustained faults and contribute to the voltage recovery of the system.

Among the commercially implemented systems the latest low-voltage–ride–through technology of GE Wind (ref. 94) can be mentioned.

Figure 25: Crow bar switching to protect converters of Type C wind turbines during grid faults



Source: ref. 80: Soens, J. et al. Interaction between Electrical Grid Phenomena and the Wind Turbine's Behaviour. Proceedings of ISMA 2004

Wind turbines of Type D offer ride through capability, which is achieved by applying specific control strategies to the inverter. For example, a description can be mentioned of the behaviour of the system applied in Enercon wind turbines, which is given in ref.95.

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[28] Private communication, Siemens Bonus, June 2005

5.4 Advanced wind energy technology solutions for grid integration

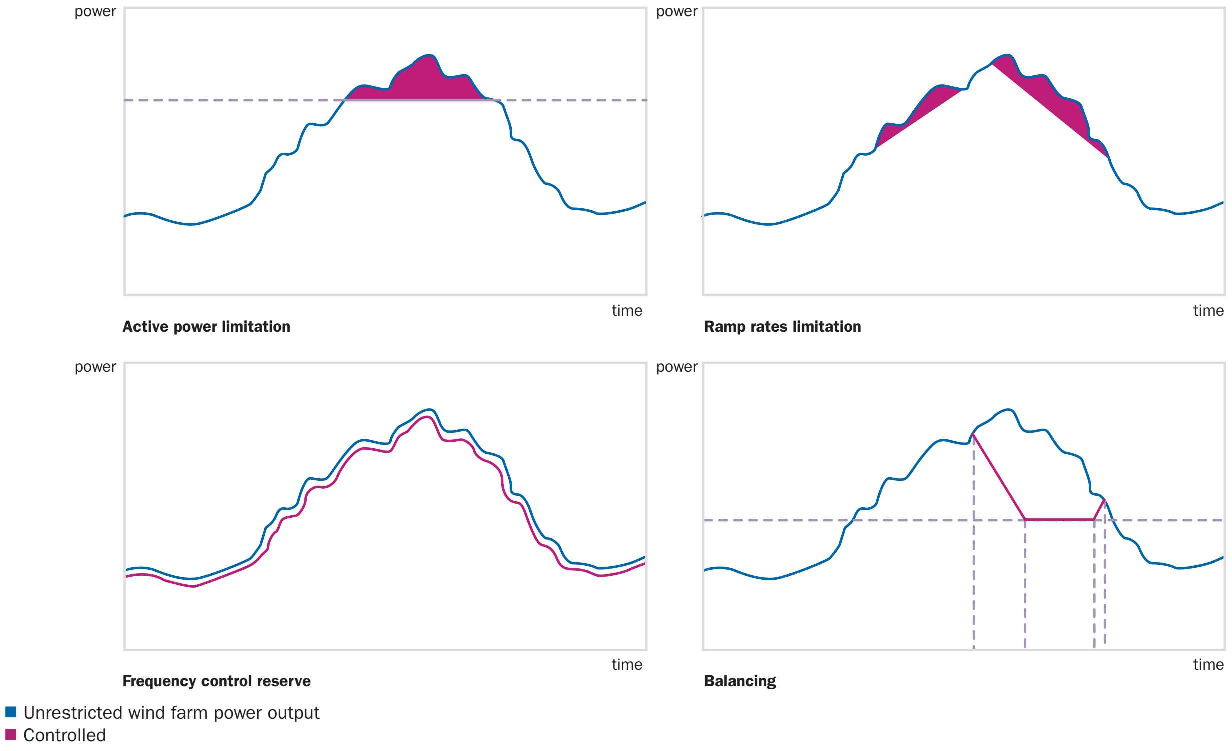
Grid codes discussed in the previous paragraph impose requirements on wind farms at the point of network coupling. Grid code compliance is partially achieved by wind farm controllers, but individual wind turbines sometimes have to fulfil certain requirements as well.

Wind farm operational monitoring and control in more advanced wind farm concepts is performed by SCADA[29] systems. A data acquisition system records the main parameters from the individual wind turbines and from the point of network coupling. The measured values are then used to determine the optimum set points for the individual wind turbines for any network and weather conditions.

This method of centralised monitoring and control, based on advanced information and communication technology, enables wind farms to perform various control functions of conventional power plants. In this way, virtual power plant properties (ref. 72) are achieved. Major important control functions are :

- **Voltage control:** In coordination with transformers tap changers voltage control is ensured by a wide range of fast reactive power control. The application of wind turbines of type D allows reactive power supply at low wind speeds and even during wind calms, when the wind turbines can be operated as phase shifters.

Figure 26: Different modes of advanced control of wind farms. The blue line shows the unrestricted wind farm power output (determined by wind conditions). The red line or area shows the controlled mode of operation



Source: K. Rohrig, ISET

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[29] Supervisory Control and Data Acquisition

- **Active power limitation** is achieved by curtailment of wind farm power output above a predefined set point. This, of course at the cost of losing energy.

- **Ramp rates control.** This type of control is in principle similar to active power limitation, in this case with time-variable set points for both ramping up and down. The latter is a critical issue for power system security. Abrupt wind power reductions can be limited by forecasting the periods with expected high negative gradients. In such cases, wind farm output is reduced in advance to limit the power gradient to a value which can safely be accommodated by the power system.

- **Balancing (primary and secondary frequency control)** is achieved by controlled reduction of active power output to a predefined level and for a predefined time period by either pitch control of all or several wind turbines, or by disconnection of some wind turbines in the wind farm. Upwards control can be provided by partly curtailed wind farm generation, kept within a pre-defined capacity band and made available within seconds. The potential reserve power of a wind farm can be determined based upon short-term forecasting and power output measurements of reference wind turbines, which are left to be operated unrestrictedly. Providing balancing and control with wind turbines means losing production that has no fuel component and costs. It is therefore not the first or most frequent option to be used in a power system, but very often can be applied in critical situations.

More detailed explanations of the principles and examples where they have been implemented can be found in the refs. 81, 107, 98. These examples and simulations show that it is technically feasible for wind farms to provide necessary frequency and voltage control, and assist to keep the system in stable conditions.

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5.5 Conclusions

Grid codes

It is evident that clear rules are needed to ensure that the grid keeps operating well and safely when generators are connected. In this respect the wind energy technology has shown that it can do what is technically required to maintain system stability.

Grid codes and other technical requirements should reflect the true technical needs and be developed in cooperation between TSOs, the wind energy sector and truly government bodies. Often grid codes contain very costly and challenging requirements (such as fault-ride-through capability and primary control) that have no technical justification. They are often developed by vertically-integrated power companies, i.e. within companies in competition with wind farm operators, in highly non-transparent manners. Furthermore, there are continuous changes of grid codes, technical requirements and related regulation, often introduced on very short notice and with minimum involvement of the wind power sector.

The technical grid code requirements and regulations vary considerably from country to country. The differences in requirements, besides local 'traditional' practices, are caused by different wind power penetrations and by different degrees of power network robustness. Wind turbine manufacturers would prefer less diversity of the regulations, although they are capable of complying with different regulations.

Some parties – especially TSOs – are pleading for a harmonisation of grid code requirements (ref. 114). However, at this point of time it is questionable whether there should be harmonised codes in view of the large diversity in power systems and wind penetrations. Furthermore it is questionable how strict the regulations should be for wind power plants. For example, it is more economic to provide primary and secondary control from conventional power plants, and wind farm operators should be demanded to provide such service only in cases where limits in existing reserves are foreseen for some critical situations. Another example of economic thinking would be to fulfil the requirement for reactive power by installing and controlling devices such as FACTS directly in the transmission network. Concerning the subject of fault-ride-trough capability the most acceptable and economic solution would be to moderate the requirements in areas with low wind power penetration.

As a rule, the power system robustness and penetration level and other generation technology should be taken into account and an overall economically-efficient solution should be sought. Costly requirements should be included only if they are technically required for reliable and stable power system operation. The assessment of the need for requirements should be made by government bodies or TSOs that are fully separated from any generation activities, to avoid biased decisions. Wind turbine manufacturers are keen to establish a close working relationship with grid operators, customers and regulators to find acceptable compromises (ref.96).

Beside the technical requirements, there is the issue of interconnection practice. There is a need for a transparent method to define the maximum interconnection capacity at a given network point as well as a definition of the maximum time for the TSO or DSO to perform relevant studies. Such method could ideally be defined by a neutral authority, for example a regulator (ref. 1 chapter 7).

Grid compatibility of wind power plants

Recent wind farm designs incorporate monitoring and control features, which – in principle - enable them to perform various control functions of conventional power plants. In this way, virtual power plant properties are achieved. Such properties could enhance the integration possibilities of wind power at a large scale.

It should be remarked though that, since only recent wind turbine technology is capable to vary frequency response, the grid code requirement of participation in primary and secondary reserve is not suitable as a general provision. Such a requirement could be in conflict with priority dispatching, attributed to 'non-programmable' renewable energy sources. For wind power, the priority in the dispatching can be considered to be much more relevant than participation in primary or secondary reserve.

■ Dynamic system studies provide basis for improved connection practices of wind power

In general, from dynamic system studies carried out for various countries (Denmark, Germany, Spain) it is concluded that power systems dynamics are not a principal obstacle to increasing the penetration of wind power, provided adequate measures are taken both in wind turbine technology and in the operation and technology of the grid. In particular, required technical measures for wind power plants as formulated in the grid codes are based on the results of these dynamic studies.

R&D should continue to further improve the knowledge on dynamic interaction of system and wind power plants. Also, continued research work is needed to improve the dynamic models for the latest wind turbine types and for entire wind farms. Such modelling efforts become increasingly important because several TSOs ask wind farm developers to submit a dynamic simulation model of the wind farm before granting connection permits, in order to carry out dynamic grid integration assessments.

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6 Improving the grid infrastructure for large-scale wind power integration

6.1 General

Adaptation of the grid infrastructure is a necessary step on the way to large scale wind power integration. The majority of European transmission systems have been developed in the second half of the last century. These systems were designed and built up in a compartmental way, confined to countries or network areas. Interconnection with neighbouring systems served primarily to increase reliability or to deliver frequency support in case of contingencies within the UCTE system. National TSOs and regulators deal with grid issues and balancing and power exchange, in a way that is determined by national legislation and the grid topology, geographical situation and historical developments.

Market, technology and environment bring along fundamental changes and challenges for the European transmission network. One of the major drivers is the emerging internal electricity market in Europe, requiring sufficient transport capacities between regions and nations to enable effective competition in the power market. The liberalisation offers the possibility for trade and hence balancing power on day-ahead and even intra-day markets with additional opportunities for settling fluctuations from large wind farms.

Thus, making the grid more suitable for increased transnational electricity transport is also in the interest of large scale integration of wind power, as well as serving a purpose to achieve a properly functioning internal market. Furthermore, the specific nature of distributed and variable-output generation necessitates development and implementation of new technology and grid management concepts.

Adaptation of the transmission infrastructure to the future needs is a complex process and is subject to strategic long-term planning. The objective of this report is to identify the elements of the agenda of the wind power sector in this strategic grid planning.

In a first approach these elements are divided into:

- **Short term:** optimisation of the utilisation of the transmission network;
- **Mid-and long term:** creation of Trans European Transmission Networks (TEN-E) and Europe wide offshore grids.

A number of specific aspects have to be taken into consideration in view of planning network upgrades and extensions:

- Long lead times in view of the planning procedures
- Network upgrade is a capital intensive activity
- Costs cannot be allocated to a single generating technology
- Planning of grid and planning of wind power are often independent processes
- Wind power connection technology possibilities: alternative solutions to defer grid reinforcements, such as the use of wind turbines with expanded MVAr capability
- Cost-effectiveness of wind power integration can be increased substantially by transnational approach

6.2 Short-term: optimal use of the present network with wind power

In the short term, and at relative low levels of wind penetration, transmission network upgrades facilitate wind power integration and coincide to a large extent with methods for congestion management and optimisation in the transmission system.

Transmission congestion occurs when the demand for a transmission path exceeds its reliable transfer capability. Such overload situations are investigated with help of so-called static load flow calculations. In a transmission system there is potential congestion on many transmission assets. When this congestion reaches a given level there will be an economic imperative to reinforce that asset. For a cost effective outcome the annualised capital cost of the reinforcement will be less than the annual operating costs[30] imposed by these constraints.

When a network congestion occurs, the system operator curtails generation in order to protect the system. For wind power plants, the existence or risk of transmission congestion, even if only for a few hours per year, may prevent a new wind farm coming on-line, unless the wind farm owner agrees to finance necessary transmission improvements to the benefit of all users, the cost of which may make the wind project uneconomic. Consequently, a significant number of high quality wind resource sites cannot be developed because developing these wind projects could increase transmission congestion, and there is insufficient available transmission capacity to fully accommodate the wind plant. Some TSOs apply temporary curtailment of wind power output in critical situations. This however should be regarded only as a short-term solution.

Network congestion is a phenomenon that can usually not be assigned to a particular technology, because many operators make use of the same grid and because the flow of electricity is determined by the law of physics.

In the few areas with large concentration of wind power, congestion in general occurs during strong winds. It can be classified (ref. 23) into low load and high load situations, which determine the urgency of required countermeasures.

- Congestions during periods of low load are induced exclusively by wind and require network reinforcement, such as renovating existing overhead lines or construction of new ones. If the reinforcement is delayed, further development of wind power in these regions will be obstructed or else the network should be operated with help of generation management only.
- Congestions during periods of high demand are a consequence of both high wind power supply and high conventional power generation. In such situations, power output of conventional generation exceeds the share of the load not covered by wind energy. The congestions can be solved by regulation of the output of conventional generation, with cost implications.

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[30] These annual costs can include: costs of losses, costs of energy constrained off the system, vs. costs of energy constrained on, costs of carrying additional capacity/reserve, which could have been provided through the transmission constraint [Econnect].

Wind energy will not necessarily increase existing transmission bottlenecks, although in practice it can occur. For instance, in the UK most demand is in the South and much of the existing generation and new wind generation are located in the North of the country, hence transmission bottlenecks are enhanced on the existing system. In the Republic of Ireland most generation is in the Dublin area and the demand in the West is fed from Dublin. Initial onshore wind power projects in Ireland – if primarily sited off the East coast - will therefore generally reduce transmission bottlenecks[31].

In general, network congestion measures can be classified into[32] :

A. soft measures, such as improvement and harmonisation of operational approaches or standards relating to the definition of technical limits, to the way in which different sources of operational uncertainty are taken into account, to tolerances regarding short-term overloading of network elements;

B. investments other than the construction of new lines, such as implementation of power flow controlling devices in conventional or FACTS technology, or the reinforcement of weak spots of existing interconnections;

C. construction of new lines and substations, including projects that have been identified as projects of common interest in the context of the “Trans-European Networks” programme (see Section 6.3)

Typical additional congestion measures required at increasing levels of wind power penetration can be classified into three corresponding categories.

A. Soft measures

- Optimisation of the utilisation of power lines assisted by temperature monitoring
- Improved cross border power exchange procedures
- Improved grid management of distribution systems

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The following example illustrates the intensified utilisation of lines assisted by temperature monitoring:

The German industry norm DIN EN 50182 stipulates the nominal transfer capacity of transmission lines at an ambient temperature of 35°C and a wind speed of 0,6 m/s. However, if a wind power induced transmission congestion would occur, ambient conditions will definitely be quite different from those values. High levels of wind power production logically correspond to periods with strong winds, where transmission lines are better cooled by wind. Moreover, since strong winds usually blow in winter, ambient temperatures are much below 35°C. If critical line sections are constantly monitored, it would be possible to increase transmitted currents by 15-30% during the congestions.

B. Investments other than construction of new lines

- Implementation of FACTS for additional voltage management
- Utilisation of fault current limiters (ref. 129)
- Reinforcement of specific interconnection points

C. Construction of new lines

- Reinforcement of existing specific lines and grid components as a consequence of power flows especially from regions with high wind resource
- Grid extension to remote resourceful areas (e.g. offshore)

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[31] Communication by Econnect (UK)

[32] Congestion report 2001.

6.3 Mid- and long term: transmission and interconnection on the European level

6.3.1 Wind power and the TEN-E priorities

Technically, a functioning market place for electricity presupposes an adequate infrastructure in order to facilitate free trade. Historically, transmission capacity among UCTE countries and even more between the UCTE and other synchronous zones is low. The Trans-European Networks for Energy (TEN-E) offer an appropriate vehicle to foster wind power integration. The aim of Community action for the development of Energy TENs is to contribute to:

- effective operation of the Internal Market in general, and of the Internal Energy market in particular;
- strengthening economic and social cohesion by reducing the isolation of the less-favoured regions of the Community;
- reinforcing security of energy supply.

The revised TEN-E Guidelines of 2003 (ref. 118) clearly acknowledge the integration of wind power into the European power systems as an additional driver for the development of European transmission infrastructures. The TEN-E guidelines form a useful framework for grid projects of European interest, including the integration of wind power. The procedures established by the guidelines could be useful in fostering cross-border coordination between Member States of interconnector projects in combination with wind farms projects. However, the budget allocated to the TEN-E programme is very limited.

Chapters 3, 4 and 7 demonstrate that aggregation of spatial dispersed wind power output is advantageous for economic integration of wind power in a large network. Expressed in simple words, the wind is always blowing somewhere, which smoothes fluctuations, and enables more accurate short-term forecasts. Hence, in order to enable a high wind power penetration level, continental-wide smoothing effects must be utilized to the extent possible. For this purpose an improved trans-European transmission infrastructure is essential.

The European Commission funded COD[33] project concluded that specifically for wind power this applies to the following categories of improvements:

- high-voltage transmission links between countries (currently getting attention in the TEN-E action), coinciding with electric priority axes[34] (Figure 27);
- offshore transmission links interconnecting different offshore wind farm areas and load centres over long distances;
- meshed long distance transmission infrastructures for interconnecting centres of load and generation on a European scale and beyond.

The second category will receive increasing attention with increasing distance of wind farms from the shore. The third category is currently not considered an economically viable option. The reasons are the high capital costs for HVDC substations, especially offshore, and the lack of a stable political framework for such investments.

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[33] COD: Concerted Action Offshore Wind Energy Development: a EU sponsored international R&D activity

[34] Electric priority axes: PUT DEFINITION / DESCRIPTION / REFERENCE

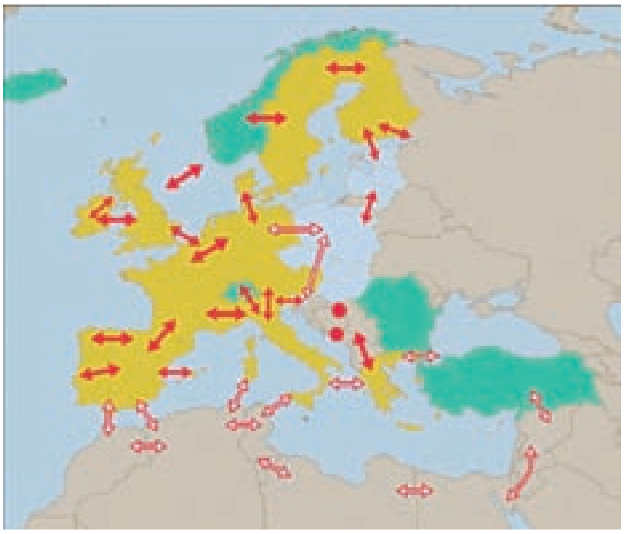
6.3.2 Cross-border transmission, interconnection

Cross-border transmission of wind power appears to be less of a technical issue than a trade and market issue. This is because cross-border trade is neither free nor fair, and is still largely defined by vertically integrated power companies. The problems wind power is facing presently are mainly caused by the fact that there is not yet a slot of cross-border capacity for variable-output power from renewables (ref. 120). Making such a slot available would enable wind power to be traded cross-border in a fair way according to the internal electricity market principles. This is currently obstructed by the competitive interests of other generating sources, regional or national oligopolies, who may also control access and own the transmission lines.

The COD project concluded on this issue: *"While power transmission within a control area is regarded as a technical responsibility of the TSO, the allocation of capacity for cross-border transmission is organized differently. Currently, the allocation of cross-border capacity happens in an uncoordinated way. In most cases it is not market-based. While the European RES-E directive requests priority dispatch for renewables to be implemented in the national regulatory frameworks, there is no such notion as priority allocation of cross-border capacity for electricity from renewables. According to the principles of the internal electricity market this allocation should be market-based.*

For wind power to be an efficient player in this internal European electricity market, tools for short-term as well as seasonal predictions for wind farm output are essential. In view of the decreasing forecast accuracy with increasing forecast horizon, wind power should be traded on power markets as close to real time as possible".

Figure 27: Electric priority axes of the TEN-E



Source: http://europa.eu.int/comm/ten/energy/documentation/index_en.htm

The allocation of cross-border capacity for trade close to real time would be possible by improving the member states day-ahead and intra-day markets for electricity as indicated in Figure 28. This means that a part of the available transfer capacity would be allocated to power exchanges and intra-day markets. Power exchanges of different control areas could then use this capacity as an instrument for equalizing their national markets (Stage 1). In the following step, intra-day markets could be coupled by allocating cross-border capacity to make power from different control areas available for balancing (Stage 2). The results would be equalized market prices between neighbouring markets and generally a lower price volatility. For the international trade of wind power it is essential to make the market coupling mechanisms available as close as possible to real time.

The technical possibilities for the cross border transmissions are determined by the so-called net transfer capacities NTC between the countries. Characteristic values for the NTC are published by ETSO twice a year, namely, for peak hours at a working day in winter and in summer[35].

The main developments and bottlenecks on international interconnections within and at the frontiers of the UCTE system have been identified in detail in the UCTE System Adequacy Forecast 2005 - 2015 (ref. 145).

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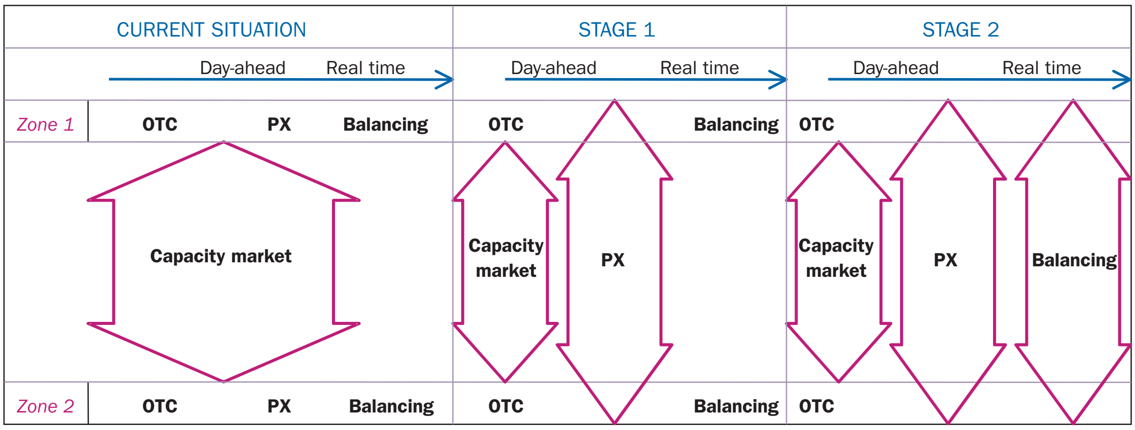
[35] A complete overview of NTCs for all boundaries between ETSO members is provided as tables and as a map at the web site of ETSO http://www.etso-net.org/

Figure 28: Stages towards improved linkage of European member state wholesale markets and balancing markets



OTC = Over-The-Counter Markets
PX = Power Exchange

Source Meeus, ref.119

Within the COD project (ref. 117), participating countries have made their observations about the NTC in view of the integration of offshore wind power. They identified a series of primary needs. This was looked upon mainly in view of the expected offshore wind energy expansion but applies to joint onshore and offshore wind power as well as the general functioning of the internal electricity market:

- Higher transfer capacities between Nordel and UCTE, mainly to cope with wind power developments in the Nordic area (primarily Denmark) and Northern Germany, and the balancing with hydro power plants in Norway.
- Poland has a high wind energy potential but a low power import capacity.
- Transmission bottlenecks within the UCTE exist at the northern borders of Spain and Italy and on the Balkan are hampering a potential trans-continental wind power balancing making use of the Europe-wide complementarity of wind speeds Strong transmission lines connecting Western and Central Europe to the Mediterranean Countries are a first necessary condition in a long-term strategy for a transcontinental exchange of power.

The above observations are in line with the European TEN-E programme where nine axes for transmission reinforcement have been identified (Figure 27) including

- reinforcement of transmission lines in the BeNeLux region, France and Germany (EL 1),
- reinforcement of connectors from Central and Western Europe to the Balkan the Mediterranean states and Portugal (EL 2, EL 3, EL 4),
- increase of transmission capacity between UCTE system, UK and Ireland (EL 5, EL 6),
- creation of a Baltic transmission ring (EL7),
- increase of transmission capacity between Germany and Austria and the new Central European member states of the EU-25 (EL 8),
- creation of a Mediterranean transmission ring connecting Southern Europe to Northern Africa and the Near East (EL 9).

Although the integration of offshore wind energy has been one of the rationales for the definition of the priority axes EL 5, EL 6 and EL 7 within the North Sea and Baltic Sea regions in the TEN-E guidelines, they do not include the need for a strong trans-continental transmission lines for grid integration and balancing of wind power.

6.4 Long-term: Europe-wide offshore grid and trans-European overlay grid

6.4.1 European super grids for offshore wind power

Transportation of substantial amounts of power from offshore wind farms to load centres all over Europe necessitates the development of Europe-wide offshore grids and trans-European overlay grids. The COD report reviewed a number of studies that investigate the implementation of offshore networks. While Watson (ref. 131) looks at a limited grid in the Irish Sea, Dowling (ref. 130) and Czisch (ref. 115) propose the development of trans-European super grids. Figure 29 outlines how such a super grid structure could be used to collect energy from offshore wind farms. Czisch goes a step further in his transnational renewable power flow modelling looking for an optimisation for a future electricity supply (ref. 116), including the use of an overlay grid connecting Northern Africa, Europe and the Middle East (Figure 30).

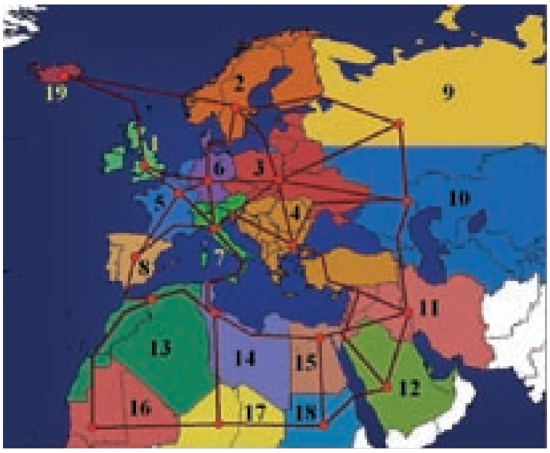
The proposed scenarios require high investments in the grid infrastructure. Nevertheless, the above studies promote these scenarios as the economically most promising long-term options (several decades) for an energy economy based on renewable sources with a large wind power fraction. For example, Giebel et al (ref.133) show that even considering the cost of cables to Europe, it could be cost-effective to use excellent wind sites on the North African Atlantic coast or at very windy sites in Egypt, in combination with sites onshore in Europe.

Studies of offshore transmission grids in the short and medium term naturally less visionary. The option of interconnecting offshore wind farms via meshed offshore grids has been studied or explored for the UK (ref. 134), the Netherlands (ref. 132) and Germany (ref. 89). Clustering of wind farms into a limited number of offshore substations is considered as an option, not only for reduction of connection costs but also to reduce environmental impacts. In the German Dena study, (ref.89) HVDC overlay lines onshore are considered for transporting offshore wind power to the load centres in the country after 2015. However, as long as connections to substations onshore are feasible, it is not anticipated that clustered offshore wind farms will become interconnected to long-distance or meshed transmission grid infrastructures offshore.

Figure 29: Vision of high voltage ‘super grid’ to transmit wind power through Europe

Source: Dowling and Hurley, ref.130

Figure 30: **Schematic representation of potential electricity transmission paths for an intercontinental overlay transmission system**



Source: Czisch 2004, ref. 115

6.4.2 Technical solutions for the offshore grid

Compared to onshore, offshore wind farms will have large power capacities with sizes comparable to conventional power plants. Modern transmission technologies operating at high and extra high voltage levels will be required in order to transmit high levels of power over longer distances (ref. 121). Two main types of offshore transmission systems exist, based on either alternating or direct current (HV-AC or HV-DC).

For wind farms close to shore the HVAC system offers the best solution, as it provides the simplest, least expensive and most proven technology for grid connection, and is similar to the transmission network used on land. However, as transmission distances increase, the losses from the HVAC system increase significantly. To avoid ineffective operation, AC cable length should be limited to a length of approximately 120 km (ref. 121). The break even distance depends on the cost developments and will move closer to the shore with decreasing HVDC system costs.

Conventional thyristor based HVDC technology has historically been used for super grid point to point power transmission. In a multi-terminal super grid system that will be required for wind farm arrays but is currently not cost efficient. Recent advances in HVDC technology using IGBT based converters seem to offer a solution and facilitate cost effective construction of multi-terminal HVDC networks. These modern HVDC-IGBT systems offer clear technological advantages, especially in the area of controllability and efficiency, though their present transmission capacity is still too small to connect large amounts of offshore wind power capacity to the grid. A specific advantage of HVDC systems is reactive power control capability, favouring grid integration and system stability. The technical and economical aspects of offshore transmission systems are being actively investigated by the supply industry and by electric power companies in order to be ready with the most cost-effective solutions, when large scale offshore wind power takes off (refs. 122,126,125, 127,128).

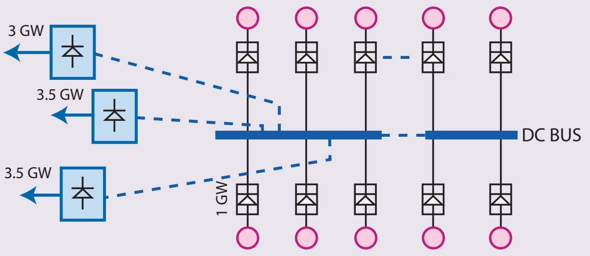
Construction of the offshore super grid would be on a modular basis and the fact that wind farms will be able to operate collectively at variable speed, frequency independent of the land-based grid, is expected to optimise turbine generating efficiency and offset losses incurred as a result of the increased transmission distances. At first, large multi-GW offshore arrays would connect to nearby networks before being modularly extended and ultimately interconnected. A further advantage of this system will be the full controllability of power flows that will eventually allow an ‘all-European’ market for electricity, including wind power.

Concept of 10 GW offshore connection

This conceptual 10 GW project conceived for installation in the North Sea consists of twenty wind farms of 500 MW, each consisting of one hundred 5 MW wind turbines. Hypothetically, the farms are installed in the North Sea. Each of the twenty wind farms is connected, via an AC-net, to a ±500 kV HVDC system installed at each branch. The HVDC-systems convert the AC power to DC, which is fed into the DC bus system. This bus system, which connects all the farms, is laid out as sea cable.

The occupied sea area of a single wind farm may be around 15x15 km^2, with a distance of 1.5 km between each turbine. A platform containing a ±500 kV current rectifier of 500 MW will be built next to each wind farm. The rectifiers are adapted to offshore environment, and will cost approx. €55,000 a piece, totalling 1.1 Million €. In order to transmit the energy from the 20 wind farms, a DC bus bar connects each farm with the onshore converters. The onshore converters could be established in major consumer areas such as London, Rotterdam, and Bremen.

Figure 31: Concept of 10 GW offshore connection



Source: SEAS, Grid Study 2003, Airtricity

The DC bus system is designed to transmit the rated power of 10 GW over its length. This requires 16 parallel cables with a total length of 1,000 km (4 per pole). Each cable has a capacity of 625 MW. The total cost of the cables that connect the DC bus bar to the mainland will amount to approx. 5.2 Billion Euro. Based on a more detailed investigation of the wind farm output patterns, it may be possible to reduce the size of the DC bus system.

Figure 31 illustrates how the current inverters placed on land are connected to the DC bus bar located near the wind farm. In the configuration with one 3,000 MW (200 M€) and two 3,500 MW (€240 million each) current inverter/converter systems on land, the total cost of the HVDC transmission system amounts to approx. 7 Billion Euro (€700,000/MW). If HVDC-light technology is used instead, the cost of the plant will be 25% higher. The mentioned costs are estimates, giving an indication of the financial implications. Prices are based on numbers from ABB and own figures. [SEAS Wind Energy Centre]

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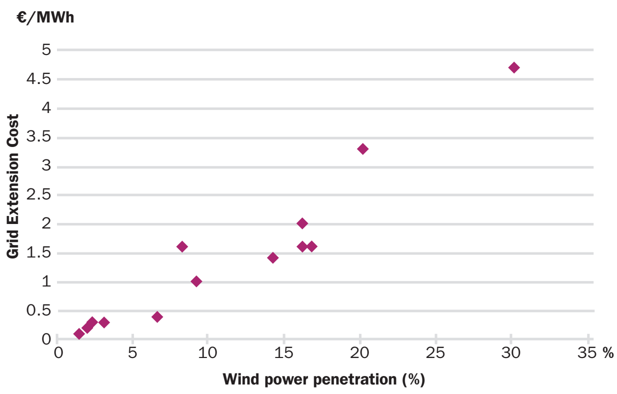
6.5 Transmission grid upgrade costs: findings from national grid studies

6.5.1 Method of cost calculation

The consequences of putting more and more wind power to work in the grids have been studied in several European countries and reviewed in the final report of the European Commission funded RE-Xpansion project (ref. 136). The national studies quantify grid extension measures and associated costs caused by additional generation and demand in general and wind generation in particular. Factors influencing the costs include measures for increasing generation capacity to meet demand (in general) and (in particular) necessary measures for large-scale wind integration. The analyses are based on load flow simulations of the corresponding national transmission and distribution grids that take into account national different scenarios of wind integration utilising the most favourable wind farm sites. Typical calculated values of grid extension costs normalised per MWh produced wind energy are plotted against the average wind energy penetration in Figure 32.

Figure 32: Estimated additional costs of grid extension as a function of wind energy penetration



Source: Auer, ref. 136

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Grid extension/reinforcement costs as calculated by such studies caused by additional wind generation are in the range of €0.1 to €5/MWh wind, equal to approximately 10% of wind energy generation costs for a 30% wind energy share. Costs depend on the wind penetration in a system. These costs appear to be in the same order of magnitude as the additional costs for reserves in the system to accommodate wind power (see Chapter 4). Further studies and a standard methodology are needed to establish a reliable empirical relation between grid extension/reinforcement costs and wind energy penetration.

There is an astonishing lack of interest from grid operators, conventional power producers and international institutions such as the IEA as well as from the European Commission to study the cost of grid extensions and reinforcements for all other technologies than wind power. It must be a minimum requirement that similar studies are carried out for other technologies in order to make proper cost comparisons. This applies for studies about the balancing costs of conventional power too.

The proper allocation of the grid extension costs is a subject that is discussed in Chapter 9.

6.5.2 Details from selected national studies

Details from a number of studies are given below.

■ **UK** *(ILEX 2002, ref. 137)*

For the North Wind Scenarios (share offshore: onshore = 50:50) the following (empirical) additional transmission and distribution grid extension cost data have been derived:

- 20% penetration: €3.3/MWh (wind)
- 30% penetration: €4.7/MWh (wind)

These results are based on comprehensive load flow analyses on the UK transmission and distribution grid for different scenarios of wind penetration up to 2020. The domestic private consumer cost of power is about €130/MWh, not including any carbon-abatement. Thus wind farm interconnection costs represent about 2.5 to 3.5% of consumer cost, which is not significantly different from similar costs for new major central generation technologies. It is important to note, however, that similar costs would occur for all types of generation, not only for wind power.

■ **France**

According to Verseille 2003, (ref.138), the French national transmission and distribution grid could cope with 6 GW of wind power capacity with only minor grid extension work; however if the capacity were to grow 14 GW it would cost €800 million to improve the network. This would equal annual wind generation of 35 TWh (8.1% of total French generation), i.e. €1.9/MWh wind generation allocated to grid extension.

■ **Netherlands:** *Connect 6000 MW*

The Connect 6000 MW study (ref. 140) gives rather precise time schedules for the necessary grid reinforcements. In the optimistic case, 6000 MW could be accommodated by the transmission system in 2012 whereas in the pessimistic case the maximum injection capacity will remain limited to 2000 MW by 2018. The costs for these grid reinforcements are estimated to be in the range of 281 million Euro (all overhead lines) to 839 million Euro (30% of the new lines underground). Transmission bottlenecks become most significant when power is exported to Germany and Belgium. All in all, the infrastructure investments due to wind to comply with the 2020 goal of 6000 MW offshore wind power are estimated to be between €200 and 500 million, depending on the development scenario. (i.e. around €1.1 - 2.2/MWh). The value is approximately 4% of the investment of the installation of 6 GW wind energy, which is estimated at €10 billion.

■ **Austria** *(Consentec 2003 ref. 142, Herbert 2002 ref. 143, GreenNet 2004)*

For Austria, different scenarios of wind integration are simulated for the year 2008 (according to the expected range of installed wind capacity in the national electricity law). For the lower level of 576 MW installed wind capacity (i.e. 2.1% of domestic consumption from wind generation) in the year 2008, grid extension cost allocated to wind is calculated to be €0.3/MWh. For the upper level expected in the year 2008 of 800 MW installed wind capacity (i.e. 2.9% wind generation), a slightly higher value is derived. Assuming an installed wind capacity of 1700 MW in the year 2020 (6.4% wind generation), additional grid extension/reinforcement cost for wind are calculated to be €0,4/MWh. In Austria, there has been a debate about the need for major transmission grid reinforcement for many years or even decades; this is not just for wind integration, but for all power supply. A suggestion is an open loop on the 380 kV-level between Südburgenland – Kainachtal (around 70 km). The proposed costs are about €120 million. Only part of these costs can be allocated to wind generation, since this transmission line is strategically important anyway for the conventional electricity markets in the next decades.

■ **Poland** *(PSE 2003)*

Based on this Polish study (PSE 2003, ref. 144), assuming up to 2.8 GW installed wind capacity, no reinforcement in the network is considered necessary. Up to 4 GW, a few upgrades on the Polish transmission grid have to be conducted (e.g. new EHV/110 kV transformers). Between 4-5 GW installed wind capacity (and corresponding wind generation), problems occurring especially in off-peak summer days could be solved by using export and hydro storage facilities. Between 5-7 GW, a new 400 kV transmission line connecting the northern circuit with central Poland is necessary. And finally, beyond 8 GW installed wind capacity, a second circuit of 400 kV in the north has to be installed. The corresponding investment amounts have been identified in the study cited above.

■ **Germany** *(DENA 2005, ref.89)*

The German Dena study has investigated the integration of onshore and offshore wind power until 2020. The following scenarios have been agreed and analysed: 2010 – 22.4 GW; 2015 – 36 GW; 2020 – 48 GW. Network constructions and reinforcements were identified for the key years. For the year 2015 there is a need to construct 851 km of new 380 kV overhead lines and to reinforce 392 km of existing lines. The total cost of all transmission network measures is assumed to be €1120 million. For 36 GW installed wind capacity and about 13% wind energy penetration in the year 2015 grid extension cost allocated to wind would amount to approx. €0.9–1.0/MWh.

In the long run, power injection from offshore wind parks in the rural Baltic and North Sea regions will be limited by transmission bottlenecks to the load centres: Rhein/Ruhr, Frankfurt, Stuttgart, München. Between 2015 and 2020, an additional 10.3 GW offshore wind power will be installed in the North Sea only. In order to transport this power to the load centres in the centre and south of Germany, the Dena grid study proposes a high voltage DC overlay grid. This would consist of two high-voltage DC transmission lines from the substations Conneforde and Brunsbüttel at the coast to, respectively, Dauersberg and Grafenrheinfeld. From Dauersberg the load centres in the west and south west can be supplied and from Grafenrheinfeld those in the south. The additional costs for these reinforcements have been estimated to be around €100/kW, when wind power exceeds 20 GW. The costs of network construction mentioned in the Dena study are relatively low. However, apart from purely economic aspects, there are other issues to be considered in the context of network construction, e.g. public acceptance.

■ **Denmark** *(COD ref. 117)*

In the Eltra system, a number of reinforcements of the 150 kV and 400 kV systems are planned by 2009 requiring no new routes for transmission lines. These would enable the connection of the Horns Rev B project that is scheduled for 2008. In the long run, the 400 kV system would be extended along the west coast of Jutland closing a 400 kV ring between Idomlund and Endrup. Power from offshore wind farms could then be collected offshore and injected at several points at the coast. Moreover, the output of all onshore and offshore wind farms and CHP plants could be transported via the reinforced 400 kV system. Reinforced interconnectors to Germany, Norway and Sweden and an interconnector to the Eastern Denmark could further facilitate this exchange. In order to connect the second phase of the Rødsand/Nysted wind farm and possibly a wind farm at Omø Stålgrunde to the Elkraft system, reinforcements are necessary in the southern part of Eastern Denmark. This includes the creation of a 132 kV transmission ring by interconnecting Vestlolland and Stignæsværket via a sea cable. This reinforcement has been scheduled to be ready by 2010 (ref. 135). In the long run the transmission ring in the south of Eastern Denmark could then be upgraded to 400 kV and linked to the 400 kV system in the northern part of Eastern Denmark. In the meantime also the Great Belt interconnector between Eastern and Western Denmark would be available and the connection to Sweden would have been further reinforced (ref. 135).

Spain

Infrastructure extension, lines and substations, and reinforcements directly linked to wind energy can be estimated in an investment of around €500 million in total for reaching 20 GW which is now the goal of the Renewable Energies Plan. This is approximately €2/MWh wind. This amount does not include the investment of the wind farms to be connected to the grid, which are connected to high voltage grid (>132 kV).

Improvement of reactive response of the wind farms through dynamic compensation will mainly be financed by wind farms owners. These investments can be partially recovered from the payment foreseen in RD 436/2004, for projects with fault-ride-through capabilities.

Italy

An official study on the grid capacity in Italy related to renewable energy input is not available. A technical study about connections in the Sardinia region has started in cooperation between GRTN and the relevant associations of the renewable sector. Even if the criteria adopted by the TSO were not accepted by the participants, GRTN affirmed that the national grid has the capacity to absorb new electricity input according to a gradual growth of new power generation.

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6.6 Conclusions

Upgraded grid infrastructure will benefit the whole power system.

The European grid infrastructure needs upgrading – on country and trans-European levels - to accommodate large amounts of wind power cost efficiently. However, the expansion of wind power is not the only driver. Grid reinforcements will benefit the whole power system. They are necessary to integrate other (non-wind) new generation and go a long way towards creating real competition in the emerging EU internal electricity market – a challenge currently being blocked by numerous distortions in the conventional power market as it is concluded by the European Commission's four Benchmarking Reports on the development of the Internal Energy Market.

The process of upgrading the grid systems is very complex and requires short-term and long-term measures to enable a smooth integration of wind power. Short-term measures include mainly optimisation of existing infrastructure, and so-called soft measures like adapted management procedures. In the longer term, a European super grid is proposed to accommodate large amounts of offshore wind power and to utilize continental-wide smoothing effects of wind power to a maximal extent, as well as to improve the functioning of the emerging internal electricity market. The wind is always blowing somewhere, smoothening fluctuations, and enabling more accurate short-term forecasts. Grid upgrading entails the following categories of improvements:

- high-voltage transmission links between countries (e.g. as established in the EU's TEN-E programme);
- offshore transmission links interconnecting different offshore wind farm areas and load centres over long distances;
- meshed long distance transmission infrastructures for interconnecting centres of load and generation on a European scale and beyond.

The TEN-E Guidelines acknowledge the integration of wind power into the European power systems as an additional driver for the development of European transmission infrastructures.

■ Cross-border transmission

Cross-border transmission of wind power appears to be less of a technical issue than a trade and market issue. The problems wind power is facing presently are mainly caused by the fact that there is not yet a slot of cross-border capacity for variable-output power from renewables (ref. 120). Making such slot available would enable wind power to be cross-border traded and transported in a fair way according to the internal electricity market principles.

While the European RES-E directive requests priority dispatch for renewables to be implemented in the national regulatory frameworks, there is no such notion as priority allocation of cross-border capacity for electricity from renewables. According to the principles of the internal electricity market this allocation should be market-based.

The technical possibilities for cross border transmission are determined by the so-called net transfer capacities between the countries. Based upon characteristic values for the NTC as published by ETSO and UTCE, a series of primary needs have been identified by the wind energy community (COD project) to better accommodate the handling of wind power (onshore and offshore) by the transmission system.

■ Additional grid costs

A number of national studies have determined the additional grid reinforcement requirements and corresponding costs due to wind power. Such studies perform load flow simulations of the corresponding national transmission and distribution grids and take into account different scenarios of national wind integration, utilising the most favourable sites. These country-specific studies (both in view of onshore and offshore) indicate that **the grid extension/reinforcement costs caused by additional wind generation are in the range of €0.1 to €4.7/MWh wind, the higher value corresponding to a wind penetration of 30% in the system (UK).**

When properly socialised in an unbundled market, these cost levels – even up to high penetration levels - are low.

Finally, there is an astonishing lack of interest from grid operators, conventional power producers and international institutions such as the IEA as well as from the European Commission to study the cost of grid extensions and reinforcements for all other technologies than wind power. It must be a minimum requirement that similar studies are carried out for other technologies in order to make proper cost comparisons. This applies for studies about the balancing costs of conventional power as well as for studies of grid extension and reinforcement costs.

7 Power system adequacy with large amounts of wind power

7.1 General

A question invariably addressed in studies on integration of power systems is how much installed wind capacity statistically contributes to the guaranteed capacity at peak load. This firm capacity part of the installed wind capacity is called "capacity credit". Due to the variability of wind, its capacity credit is lower than other technologies. However, there is a certain amount of firm wind capacity, which contributes to the adequacy of the power system. Capacity credit is not a term that refers to how much MW wind actually replaces, and should not be confused with the displacement of MW from other power sources which is calculated from a comparison of load factors. In that substitution 1MW wind replaces the electricity from 0.2-0.7MW of conventional generation (see box page 49).

Beside generation adequacy, power system security is depending on the adequacy of transmission. In this respect, wind power is contributing to the power flows in the transmission system, and thus plays an equivalent role (together with the other generators) in use of interconnection capacities etc.

Another aspect of system adequacy is related to the security of fuel and energy supply. Wind power makes the system less dependent on import of fossil fuels with all related volume and price volatility. Moreover in energy constricted systems, like hydro-dominated systems, wind power brings clear benefits in adequacy of energy for the power system.

This chapter briefly outlines system adequacy as defined by TSOs and addresses the interaction of wind power and the system adequacy on these different levels.

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7.2 Security of supply and system adequacy

The peak demand (or peak load) of electricity in Europe is constantly increasing. For the years to come the UCTE (ref. 145) expects a rise in the peak demand of approximately 2% per year, after 2007 the expectation is a 1.6 to 1.7% increase per year. The peak demand is a strategic parameter, because it determines the required generating and transmission capacities. As a matter of convention, for system design purposes, peak load values at specific points of time in the year are being considered, that is in January and in July.

The way the power system is capable of matching the evolution in the electricity demand is expressed in the term 'system adequacy'. The adequacy has different components:

- The ability of the generation units in the power system to match the demand (load).
- The ability of the transmission system to carry the power flows between the generators and users.

System operators have the responsibility to maintain system adequacy at a defined high level. In other words, they should ensure that the generation system is able to cover the peak demand, avoiding loss-of-load events for a given security of supply. Various national regulations regarding this "security of supply" range from 99% security level (in 1 out of 100 years the peak load cannot be covered) to 91% (1 event in 10 years).

Every country has its own detailed method to assess the system adequacy. As the whole European system is interconnected, it is logical that national TSOs harmonise their approaches, which is mainly done under the umbrella of the larger systems such as UCTE, Nordic system, UK and Ireland system (see report inlay). The assessment methods of generation adequacy can be deterministic or probabilistic, or a mix of the two. Even from a national point of view the system adequacy assessment involves trans-national issues, because at the moment of peak load there may be need to have access to power produced by a neighbouring country and the transmission system should be able to carry and direct these trans-national power flows.

The system adequacy of the UCTE system is being periodically reviewed in a 10 year forecast. From the latest review (ref. 145) we learn that: *"Generation adequacy assessment is based on the estimation of the so called "remaining capacity" which can be interpreted as the capacity that the system needs to cover the difference between the peak load of each country and the load at the UCTE synchronous reference time (so called "margin against peak load"), and, at the same time, exceptional demand variation and unplanned outages which the system operators are responsible to cover with additional reserves.*

After the generation adequacy assessment has underscored how each country could satisfy its interior load with the available national capacity, transmission adequacy assessment consists in investigating if the transmission system is sufficiently sized in order to enable the potential imports and exports resulting from the various national power balances, thus improving the reliability of the European power system".

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

In the estimation of the adequacy, each power plant is assigned a typical capacity value. This takes into account outages, scheduled and unscheduled. No plant has a capacity value of 100%, because there is always the probability that it will not be available when required. By making a system-wide reliability assessment, it is possible to rely partly on variable-output generation as well. UCTE in its forecast is also looking at increasing shares of wind power in the coming years. In the terminology of UCTE, a large part of wind power is termed non-usable power. The European transmission system operators association often overestimates the "non-usable power" fraction of wind power despite the fact that solid proof, 20 years of experience and extensive research have established, years back, the positive capacity credit of wind power. It is clear from the numbers in the UCTE report that there is not yet a proper standard amongst the TSOs for the determination of wind power's capacity credit (and hence of the so-called non-usable part of installed wind power).

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7.3 Impact of wind energy on the system generation adequacy

7.3.1 Capacity credit is the measure for firm wind power

The contribution of variable-output wind power to system security – in other words the capacity credit of wind – should be quantified by determining the capacity of conventional plants displaced by wind power, whilst maintaining the same degree of system security, with unchanged probability of loss of load in peak periods (see Box).

The capacity credit of wind has been getting special attention in many national wind integration studies, because in a way it is a 'synthetic' indicator of the potential benefit of wind as generator in the system. Sometimes the capacity credit of wind power is measured against the outage probabilities of conventional plants. A recent comprehensive overview of these studies is given in Giebel, ref. 148.

7.3.2 Capacity credit of wind power from national studies

Despite the variations in wind conditions and system characteristics among the European countries and regions, capacity credit studies converge to similar results. For small penetrations, the relative capacity credit of wind power will be equal or close to the average production (load factor) during the period under consideration. It is proportional to the load factor at the time of the highest demand. For North European countries, this is higher in winter, when the demand is higher, typically 25 – 30%. The load factor determining the capacity credit in general is higher than the average yearly load factor. The distribution of the wind during the high-load period is determining the spread of the substituted conventional capacity, for small as well as for high penetrations.

How capacity credit is determined

There are basically two different ways to calculate the capacity value of wind power: by simulation and by probabilistic analysis.

In simulation methods, the secure operation of the system is observed and analysed by stepping through time-series data using simulation models. The results should be interpreted with care since single events tend to dominate the result (ref. 148). The most significant events are special combinations of load and wind speed, especially in the high load period. In order to grasp the effect of such special combinations, a sensitivity analysis is performed, shifting the time series of wind power against the load data in steps of days. In the probabilistic method – which is the preferred method for system planning purposes - basically the availability of each power plant in the generation system is assessed. For instance, it is generally assumed that a coal power plant has an operational probability of about 96% and the probability of non-operational condition (scheduled or unscheduled) of 4%. In order to take wind power into account, its capacity and probabilities have to be introduced into the model. The probability of generation of individual wind turbines is determined by the wind regime, an assumption which automatically induces a certain correlation between the power outputs of the individual wind turbines. A realistic representation needs to take smoothing effects into account, which arise from the geographical dispersion of wind farm locations. On the base of the probabilities of individual power plants and the wind power, the probabilities of the whole generation system to cover different load levels can be derived.

With increasing penetration levels of wind energy in the system, its relative capacity credit becomes lower. However, this does not mean that less capacity can be replaced. It means that a new wind turbine on a system with high wind power penetration levels will substitute less than the first turbines in the system. This is illustrated in Figure 33 where the relative capacity credit tails off, towards a value depending mainly on the minimum load factor. For a European spatially-averaged wind, the unused or displaced conventional capacity is reduced to 9% of the installed wind capacity at 45% wind power (capacity) penetration.

Table 18 summarises the factors leading to higher or lower levels of capacity credit. The differences in results from various national studies can be better understood, when looking at these factors. For example, in the UK study-case in ILEX (ref. 137) shown in Figure 33, the capacity credit of wind is significantly higher than the one found in the German Dena study (Figure 34). This is explained by the fact that the average wind speeds in the UK are much higher than in Germany, and moreover, the assumed system reliability in ILEX (91%) is much lower than the level assumed in the Dena Study (99%).

Figure 33 also shows the differences between the seasonal capacity factors, whereas Figure 35 shows the effect of expected improved load factors in Germany as a consequence of improved technology and the utilisation of higher wind sites (offshore).

Table 18: Factors affecting positively and negatively the value of the capacity credit of a certain amount of wind power in the system

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

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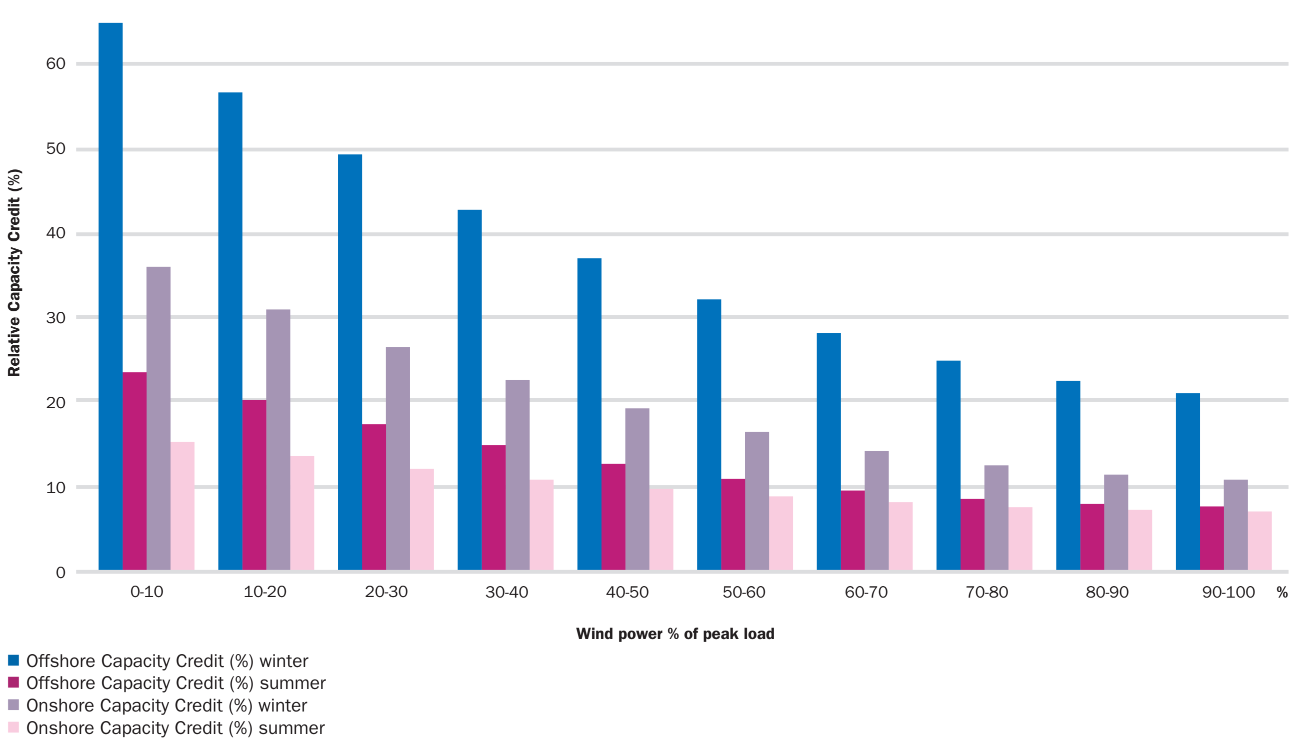
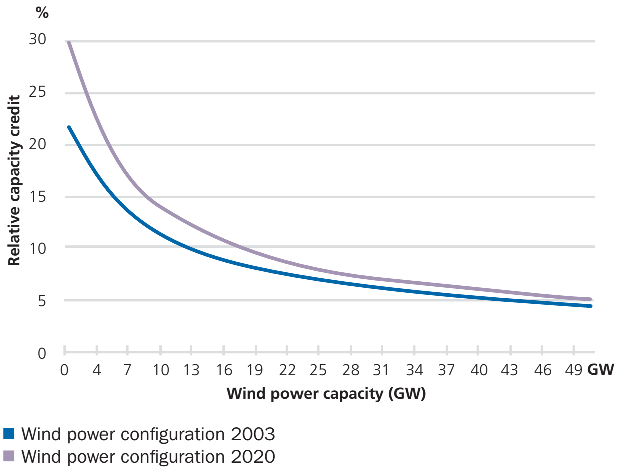
Figure 33: Average capacity credit for different values of wind (capacity) penetration for different situations: offshore/onshore, summer/winter based on Dany/Haubrich (2000) and ILEX Energy Consulting (2002)



Source: Auer, ref. 77

Figure 34: Relationship of installed wind power and capacity credit in Germany



Source: Dena 2005, ref. 89

Figure 35: Development of seasonal values of wind power capacity credit

Source: Dena 2005, ref. 89

It can be concluded that wind energy has a significant capacity credit in a power system. The aggregated capacity credit of the wind power plants in a system depends on many factors. On the one hand it depends on the characteristics of the power system in question (reliability level, flexibility of the generation mix) and the penetration level of wind power in the system. On the other hand it depends on a range of wind and wind technology specific factors such as average load factor[36], dispersion of wind plants in the system etc. The relative capacity credit decreases from approximately a value equal to the load factor at high load (25-35%) for small penetrations to approximately 10-15% at high penetrations.

Although, physically and technically, wind power has a capacity credit, in liberalised electricity markets the "capacity credit" of wind is not yet recognised.

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[36] Load factor: depends on relation between rotor size and rating of generator

7.4 Wind power and transmission adequacy

Wind power, especially when introduced on a large scale, causes an additional loading of transmission systems, because the production capacity is – similar to conventional plants - not always located in the neighbourhood of the load centres. The impact of wind on transmission systems is being investigated, mainly on national or regional level, in static and dynamic grid stability studies, as described in par.5.2. The adequacy of the network is investigated in detail with advanced grid models. Appropriate wind climate, wind turbine and wind farm models have to be used to obtain as realistic results as possible.

Basically the relationship between wind power integration and transmission adequacy is at several levels, which are discussed in several parts of this report.

- Adequate connection practices of wind power systems (Chapter 5);
- Adequate transmission and interconnection infrastructure (Chapter 6);
- Adequate transmission system operating procedures (Chapter 6).

In order not to compromise the grid adequacy at increasing penetration levels, grid codes – inspired and backed up by the conclusions of the above studies – are becoming more and more demanding, especially the required capability of wind power plants to participate in voltage support in the network and the continuation of power supply by wind farms in the event of grid faults, just like other power plants do. Assuming such capabilities are fulfilled by wind power plants, grid studies demonstrate the technically feasible levels of wind power penetration, in a given network configuration, and indicate required network upgrades and reinforcements, to maintain transmission adequacy.

A critical issue though is created by the specific situation in Germany, where at certain high wind speed / low load combinations, power flows form North to South are affecting the cross border flows and transit flows in the Benelux and cross border flows to Poland. It is very difficult to establish whether the cross-border flows are a result of inadequate interconnection between the four main supply areas internally in Germany, but the suspicion has been raised by Dutch authorities. Such undesirable situations are the result of the overall system configuration and state of operation of all units in the system, and not only of the wind power plants. These events should be managed by curtailing local conventional generation to keep system stability at the lowest cost to the consumer.

Such problematic situations are potentially compromising the transmission adequacy. Although some of the problems can be solved by modifying interconnection capacity allocations (soft measures), interconnection capacity reinforcements would be necessary in a number of locations in order to enable increased penetration levels (see par. 6.3).

The approach described above of assessing the impact of wind on transmission networks is less and less adequate, with increasing levels of wind penetration, because of the trans-national character of wind power. Although coordinated at a synchronous zone level (UCTE etc.) and at the European level, the transmission grid is largely designed and operated at national level. It will become more and more difficult to find the optimal solutions for the trans-national grid challenges, if that approach is continued.

The proper long-term designing of the transmission system has to take into account realistic cross border flows, transit flows as a consequence of the movements of large-scale weather systems over Europe and the schedules in wind power plant development.

It would be recommended to undertake transmission network studies at a European level, especially focusing on trans-national issues, to create a solid basis for optimal and economic integration of wind power. In a transmission network that takes into account wind farm characteristics, wind power plants can deliver ancillary services and possibly congestion control.

7.5 Contribution of wind power to energy adequacy and security of supply

Wind power production is replacing other energy produced in the power system. This results in improved security of supply especially when the fuels replaced/saved are limited or expensive.

Reduction of dependence on fossil fuel imports, especially gas and oil, reduces the effect of price peaks on the national economy (ref. 152, 153). Wind power can also save the use of limited energy resources. Hydro power is an example of this: there is not enough water to run the hydro power plants at full power all year. With large reservoirs, the production can be lowered in times of high wind power production and water saved to be used later, giving better adequacy in times of peak demand. Benefits of wind power in hydro dominated systems have been studied in Sweden and Norway (ref. 154, 155). In some countries, biomass is also an example of this process.

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7.6 Conclusions

Adding wind power to the existing system contributes favourably to the security of supply. Wind energy will replace energy produced by other power plants, which improves the energy adequacy of the power system. This is especially beneficial when wind is saving limited energy sources like hydro power and imported fuels like gas and oil, decreasing the effect of price peaks on the national economy.

In addition to energy, wind power can also replace conventional generating capacity. The effect of wind power on adequacy of power will be limited. When wind power produces around 5% of the electricity consumption, its relative capacity credit is equal to the average wind power produced during times of peak demand (between 20% and 35% of installed wind power capacity). At higher wind power penetration, its relative capacity credit becomes lower than the average wind power output in times of peak demand.

In addition to the above, adding wind power to the existing system is contributing favourably to the security of supply by virtue of technology diversification and indigenous production.

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8 Economic impacts of large scale wind power integration

8.1 General

When introducing significant amounts of wind power in the system, the overall cost of electricity will change as a result of the balance of benefits and costs added by wind generation. A thorough economic analysis of high wind scenario is outside the scope of this report. This chapter rather focuses on demonstrating that increasing the share of wind power in the electricity supply is likely to have a beneficial effect on the cost of electricity for the end users.

A classic method to determine the economic impacts of large-scale wind power integration is to calculate the system integration cost, as explained in paragraph 8.2. This approach is illustrated with two recent large-scale case studies, one in UK (ref. 41) and the other one in Germany (the Dena study, ref.89). The effects of cost developments for wind generation, conventional generation and quantification of social benefits from CO_2 emission on the cost of the electricity sold are highlighted. In addition to this analysis method, it is explained how a risk-adjusted evaluation of generation cost of the combination of wind and other technologies in the generation portfolio – to take account of the high year-to-year price volatility of fossil fuels – leads to a lower system integration cost of wind power.

However, wind power and other variable output renewables are not to be considered as just a direct substitute for dispatchable fossil technologies (ref. 166) and their optimal economic integration requires changes in design, operation and management of power systems.

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8.2 System integration cost of wind energy

The net economic effect of adding wind power to the system is calculated by comparing the total costs of energy scenarios with more (much) or less (no) wind power in the system. The costs of such scenarios are made up from a number of different costs and benefits contributed to different market participants. The estimates concentrate on the net overall effect, the so-called 'system cost' of integrating wind power, which will be most likely passed on to the consumers.

Basic assumptions to be made are:

- A growth of the total annual consumption and of the peak demand;
- The reliability of the supply is maintained at the same level in all scenarios;
- There is a strategy to build up the additional generation capacity to meet the projected peak demand, with a sufficient plant margin to guarantee the reliability of supply. This will allow estimation of the investment and operation costs of new generation capacity. The following has to be considered:
  - The amount of wind power capacity required in the wind scenario is the capacity that, when multiplied with the assumed capacity factor, will produce the projected share of the average annual demand in the target year. A part of this wind power capacity will reduce the need for new conventional capacity. This amount of 'firm wind power' is equal to the estimated capacity credit of wind power[37].
  - The required additional conventional capacity in the wind scenario is the amount in the non-wind scenario minus the firm wind power.
  - The modest amount of additional thermal capacity to cope with the additional variability of wind power (secondary and tertiary reserves) is likely to be provided by running a small additional amount of the remaining thermal capacity in the system in reserve mode.

The costs of the scenarios consist of the following categories:

- Generation investment costs and operating costs, taking account of the optimal balance between conventional capacity, wind power capacity and demand;
- Variable costs such as fuel costs for generation including balancing;
- Network costs (shallow and deep infrastructure costs for conventional, offshore and onshore transmission and distribution).

The total costs in the various scenarios divided by the total amount of kWh consumed should give an indication of the consumer price for electricity. Comparing these values indicates the economic effect of wind power. A fair comparison should include externalities (environmental costs and benefits) of electricity production.

8.2.1 Generation costs (investment and operation costs)

■ Conventional (thermal) plant

Generation technologies competing with wind power for economic comparison in Europe are new coal, gas (mainly in CCGT) and nuclear. Calculated per MW, investment costs and operational costs for conventional plant are the same in both scenarios. Per kWh produced, these costs are slightly lower in the wind-scenario as a consequence of a more intensive use of the conventional plants, because of the additional balancing task.

Typical 2004 numbers for thermal generation costs are given in Table 19 (from ref. 167).

One of the most volatile parameters in the cost estimate for conventional generation is the price of fossil fuel. Paragraph 8.3 deals with the risk of price volatility.

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[37] As discussed in Paragraph 7.3 the capacity credit of wind power depends on many factors, and has to be evaluated case by case, or rather country by country, region by region. For example, an all-European value of wind power capacity credit at 20 % penetration is estimated to be between 12 and 15 %.

Table 19: Generation costs (2004) of the competing generation technologies

Generation technology	€/MWh Excluding CO_2	€/MWh Including CO_2	Remarks
Gas (CCGT)	45 - 55	48 - 58	Gas prices 0.36 ct€/MJ - 0.52 ct€/MJ
New Coal	35 - 45	43 - 53	Fuel cost €10-17/MWh
Nuclear	35 - 58	Idem	Lower value public sector 6% interest rate, higher value: private sector 11%

Source: ref. 167

■ Wind power generating costs

The generation costs for wind power have to be estimated based on a careful assessment of a specific wind power production configuration and its development in time. This configuration is determined by the distribution of the installed wind power capacity over the various projected sites, and over the wind turbine technologies used. The generation costs are strongly influenced by the local wind resource (see Figure 36) and by the assumed manufacturing year (because of the reduced investment costs over time). Furthermore, for cost estimations, onshore and offshore wind have to be treated as different technologies, because of the large cost differences.

Based on an analysis of a dataset comprising of more than 3400 MW wind projects, it is concluded by Milborrow in ref. 167 that present day generation costs[38] for onshore wind power are in the range of 40-64 €/MWh, making allowance for investment and annual operation costs. There is less operational data for offshore wind energy. At the lower end of the cost range, there are the near-shore projects in the more sheltered waters, at the higher end the more exposed and deep water sites. This results in a present cost range of 68-98 €/MWh (ref. 167) for offshore wind power. Experts agree that wind energy generation costs will reduce considerably in the next decades, following a similar path as onshore wind power and also that the offshore costs reductions for the years 2010 and 2020 will be larger than onshore. On the level of reduction there is some disparity among the experts, see Figure 37. Taking a weighted average of expert opinions it is argued in ref. 167 that onshore generation costs can be expected to drop by 20-25% by 2020, and offshore generation costs up to 40%. Because of the large variety of wind speeds and other cost determining factors (such as steel prices) in the EU, these should be considered on a country or regional basis. A detailed discussion of the latter is outside the scope of the present report.

Table 20: Generation costs (2004) of wind power generation

Wind technology	€/MWh	Remarks
Wind onshore	40 - 64	Lower value: 1150 €/kW at 9.5 m/s; higher value: 800€/kW at 6 m/s
Wind offshore	68 - 98	Lower value: 1800 €/kW at 8 m/s in sheltered water; higher value 1450€/kW sheltered water at 6.5 m/s (higher investment costs in the offshore conditions yield costs within these range, because of the significantly higher wind speed)

Source: ref. 167

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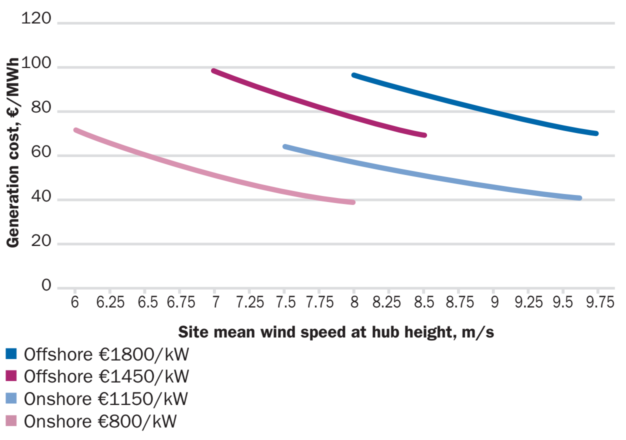
[38] Levelised costs, leading to an "annual charge" rate of 10% to take account for depreciation and interest.

Figure 36: The effect of wind speed on the generation cost of wind power



Source: Sustainable Energy Commission UK, ref. 41

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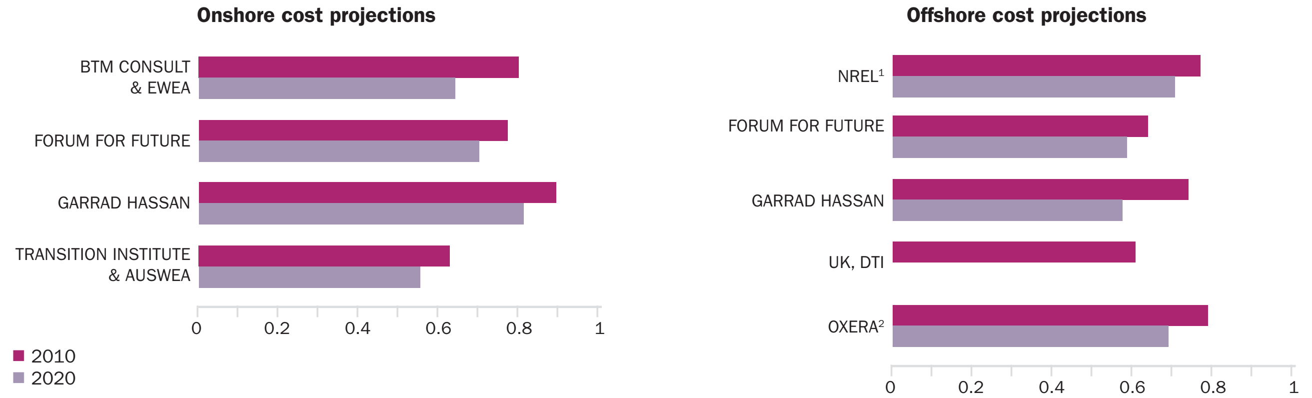
Figure 37: Expected cost reductions in 2010 and 2020 with respect to 2003 levels for onshore and offshore wind from different studies



[1] Reference year 2006

[2] Estimates from mid-range scenario

Who is who: BTM Consult of Denmark; UK think-tank Forum for the Future; UK consultant Garrad Hassan; Transition Institute/Australian Wind Energy Association; US National Renewable Energy Laboratory; UK Department of Trade and Industry; UK consultancy Oxford Energy Research Associates.

Source: Milborrow, ref. 167

8.2.2 Additional balancing and network costs

Beside generation costs, additional system costs to enable increasing wind power penetration are essentially caused by the need for additional balancing and for network upgrade.

Balancing

In both type of scenarios (no-wind versus wind) there are balancing costs to cope for uncertainties between demand and generation. The amount of additional reserves to cope for the additional variability introduced to the system by wind power has been discussed in paragraph 4.2.2. The costs as derived from a number of regional and national studies are in the order of 1-3 €/MWh (wind) and 2-4 €/MWh for higher penetrations, up to 20%. These costs can be reduced by improved forecasting and market mechanisms, as explained in Chapter 4.

■ Network upgrade costs

The issue of additional network reinforcement and extension costs has been discussed in paragraph 6.5. The cost range found for additional network costs from various national studies is 0-4.7€/MWh (wind) for wind power penetrations of up to 30%.

As discussed in Chapter 6, there are large differences in approach between the various EU countries for attributing grid infrastructure extensions to specific generation sources. The issue is illustrated by giving specific numbers for two major national studies in paragraph 8.3.

8.2.3 Quantifying the social benefits : CO_2 emission savings costs

In order to create a level playing field for a CO_2 free source such as wind energy, the social costs of avoided CO_2 from the system cost of wind should be subtracted. In dealing with these costs, assumptions have to be made on the social cost of carbon (which is different from the market price of carbon, for example in the EU Emissions Trading Scheme and currently traded at app. €20/Tonne – October 2005). The social cost of CO_2 attributed is higher than this market price. In the UK study, a mid-range value of €27/Tonne CO_2 is used. In the Dena study on the other hand, only expected auction values are used, with a rather low estimate of 12.5 €/tonne in 2020. The other element in the analysis is the amount of CO_2 emissions mitigated by wind energy. This needs careful approach because of the uncertainty about the generation mix and the technological developments.

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8.3 Case studies

The results of two recent studies are presented to illustrate the 'system integration costs' of wind power in two European countries, notably UK and Germany. The studies estimate the additional cost – termed system cost - of adding wind power to the electricity supply mix. Although circumstances and underlying assumptions are quite diverse among those studies, they both conclude that the additional system costs of significant wind penetration are modest.

The studies are assuming very low fuel prices, compared to current (October 2005) levels.

■ United Kingdom

L. Dale et al. (ref. 160), based on the extensive ILEX study (ref. 161) calculate the extra costs in 2020 of electricity to the consumer if 20% of electricity is sourced from wind, compared to a coal/gas mix. Their analysis seeks to estimate cost and benefits of large-scale development of wind power compared to using fossil fuels. The results have been updated in 2005 with a publication from the Sustainable Energy Commission (ref. 41), which analyses the effects of gas price developments and social benefits from CO_2 reductions. The study finds that the social benefit of having 20% of the nation's electricity from wind power might outweigh any costs.

Main assumptions

The UK electricity demand is assumed to grow by 17% to 400 TWh in 2020, and the peak load increases to 70 GW. Attributing an average capacity factor of 35% and a relative capacity credit of 20% to wind power, results in displacing 5 GW conventional generation with the 26 GW of wind needed to produce the 20% of the demand. In 2020, 60% of the wind generated electricity is coming from offshore wind farms. The current reliability standard of the power supply is maintained, the applied discount rate is 8% and a 15 years economic lifetime is assumed.

Cost assumptions in 2020[39]

For conventional generation (CCGT), investment cost of €580/kW and operation cost of €28/kW are assumed. The load factor is 85%, the gas price assumed €9.5/MWh (19 p/therm).

For wind power, projected investment costs onshore are €660/kW and offshore €870/kW. Operation and maintenance costs onshore are €16/kWh/year and offshore €28/kWh/yr. The additional balancing costs for wind assumed: €4.1/MWh of wind.

Transmission infrastructure costs amount to €145/kW, totalling at €2.46 to €4.7 billion. Wind connection costs are €72.5/kW or €0.87-1.45 billion. For the avoided conventional transmission connection costs a credit of €0 to 435 million is estimated in the wind-scenario. Distribution network reinforcement costs are €58/kW or €609 million.

Results

The total additional system cost with 20% wind is €4.6/MWh sold (or €23.5/MWh of wind produced). This is 5% of today average domestic electricity price (€87/MWh).

The study (ref. 160) discusses the effect of uncertainties on the additional cost of wind. For example assuming that wind capital costs do not fall and remain at the 2002 level, it adds another €2.7 per MWh sold. On the other hand, the effect of gas price on the various wind scenarios is discussed in a more recent study (ref. 41). With gas at a price level of €15/MWh (30 p/therm) (mid 2005) – 57% higher than the initial assumption – the electricity cost increase in the 20% wind scenario would only be 2.4 €/MWh. If less wind energy is added to the system (7.5% of 2010 target) with this gas price of €15/MWh, the additional system cost would be €0.8/MWh.

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[39] Values from the study by Dale are converted to Euro with exchange rate 1.45 Eur per GBP

Conservatively assuming that wind displaces only average emissions from gas-fired plant, the total annual CO_2 emission savings, corresponding to 20% wind power are calculated in ref. 41. Conventional generation of the projected 400 TWh corresponds to annual emissions of 28.4 million Tonnes CO_2. Figure 38 shows the net effect on the additional system costs, for a number of assumed CO_2 'social costs' values. It shows that the additional system costs become zero for a value of €14/CO_2 Tonne – assuming a gas price of around €19/MWh (25% higher than present 2005 price). Higher values for social costs of carbon further reduce the system cost of wind. It does not take a CO_2 value much higher than €30/Tonne to make the 20% wind scenario the cheaper option at the present gas price level in UK.

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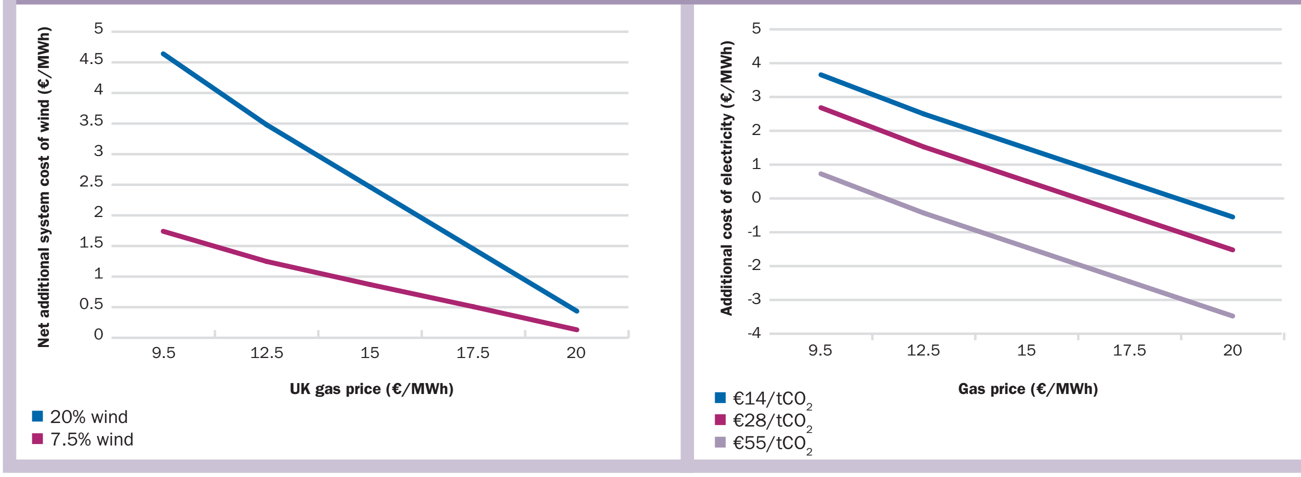
Figure 38: **Effect of gas price and wind penetration scenario (left) and gas and CO_2 price levels (right) on the net additional system costs for the end consumer. Without social benefits of CO_2, higher gas prices than 23 €/MWh would be needed to make the cost negative, but even with relatively low CO_2 prices, benefits would already outweigh the system costs of integrating 20% wind in the UK power system, given today's gas prices.**



Source: Ref. 41

Germany

The DENA study (ref. 158) quotes conclusions for the net effect on the consumer price of increasing the share of wind power from the present 5% to a level of 15%.

The results of the Dena study are not directly comparable to those of the above UK study, for a number of reasons. The Dena study only looked until the year 2015, the assumed system reliability (one event in 100 years) in Germany is a lot higher than in UK (one event in 10 years), resulting amongst other things in lower capacity credit values for wind power in Germany. The additional balancing costs are higher in Germany mainly because of less favourable power market mechanisms assumed (day ahead scheduling, see Chapter 4). Also because of the lower wind speeds in Germany, the average load factor of wind power is lower than in UK, hence more wind power capacity is needed to produce 15% of the demand.

The wind energy generation costs are quantified by using the values of the feed-in tariff, which for the developers and operators of wind farms have to cover the investment and recurring costs. Moreover, for offshore projects, the connection costs should also be covered in the higher specific feed-in tariff. In this way, the assumed generation costs are higher in the German scenario.

The assumed long term gas price is similar in the Dena study and in the UK study. The method to take the CO_2 savings effect into account is different in both studies. The German study assumes expected auction values in its calculations.

In spite of all these differences, the Dena study finds a net increase of electricity sold to consumer in the order of €3.8 to €4.7/MWh, much similar to the values found in UK. Of this amount, the fraction needed to cover necessary network upgrades to enable more wind power penetration is only minor (around 7% of the additional costs).

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8.4 Economic value of reduced risk in wind power scenarios

In the previous economic analysis, it has been implicitly assumed that wind power is substituting other generation sources in the generation portfolio. Awerbuch (ref. 166) argues that this approach does not correctly capture the economic impact of wind energy in the generation portfolio. One big economic advantage of wind power is its price stability and the hedge it provides against fuel price risk. Wind power generation costs have declined steadily over the last 25 years. Factors such as larger projects, higher energy capture by larger turbines, more efficiency in installation and economies of scale will make wind energy even cheaper in the future. The predictable cost property of wind power has a direct economic value for society as quantified by Awerbuch using standard finance theory based on the Capital Asset Pricing Model (CAPM)[40] approach: *'When added to a risky, fossil-dominated generating mix, wind and other fixed-cost renewables reduce generating cost and risk, as long as the mix can be altered over time.... This so-called portfolio effect holds even if wind costs more on a stand-alone basis. Wind's generating costs are uncorrelated to fossil costs, which means that it diversifies the mix and reduces expected overall cost and risk the same way diversification improves the expected performance of financial portfolios'.*

As an example, in ref. 166 comparative cost calculations of a DTI Year-2010 portfolio are shown, containing 11% wind with a number of optimised portfolios.

Increasing the share of wind power to more than 50% (25% onshore and 31% offshore) would result in a portfolio with the same cost, but with 50% less risk.

A more conservative alternative portfolio with 31% onshore wind, and no offshore, would reduce the portfolio kWh cost by 16%, and maintain the same risk level as the target portfolio.

Table 21: DTI targets versus optimised generating portfolios (UK 2010)

DTI 2000/2010 technology generating costs (p/kWh): Coal: 4.0/3.6 - Gas: 2.0/1.9 - Wind: 2.7/2.0 - Offshore: -/3.6			
	DTI 2010 Target portfolio	Typical optimized portfolios	
		"Equal cost"	"Equal risk"
Portfolio cost	2.96 p/kWh	2.96 p/kWh	2.49 p/kWh
Portfolio risk	.08	.04	.08
Portfolio share	71%	32%	52%
Nuclear share	16%	12%	14%
Wind share	Onshore: 11% Offshore: 0%	Onshore: 25% Offshore: 31%	Onshore: 31% Offshore: 0%

Source: Awerbuch Airtricity 2005, ref. 166

In these considerations, it is assumed that the necessary 'system' measures (network upgrade, provisions for balancing) are made to allow the corresponding wind penetrations. The portfolio-effect only affects the generation costs (par. 8.2.1).

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[40] Capital Asset Pricing Model, ref. 166

8.5 Conclusions

In this chapter we have focused on the estimated effect of wind power on the cost of the electricity sold. In principle, system integration costs of wind power are analysed by comparing the total costs of scenarios with and without wind, and calculating the consequence per kWh sold.

Generation costs constitute the largest fraction of the cost of power. Expected cost developments of wind power and conventional generation are such that in a scenario with substantial amounts of wind power, the additional costs of wind power (higher installed costs, increased balancing, network upgrade) could be outweighed by the benefits, depending on the cost of conventional power and fossil fuels and uranium. The expected continuing decrease of wind power generation costs (reduction of 20% for onshore and 40% offshore in 2020 compared to 2003 levels) is an important factor. The economic benefit of wind becomes larger when social benefits of CO_2 emission reductions, health effects and environmental degradation are taken into account.

Large national studies in UK, Germany and Denmark confirm that system integration costs, under the most conservative assumptions (gas price does not increase substantially, low to zero social benefit of CO_2) are only a fraction of the actual consumer price of electricity and are in the order of magnitude of €0 to €4/MWh (consumer level). It is recommended that similar studies are undertaken at European level.

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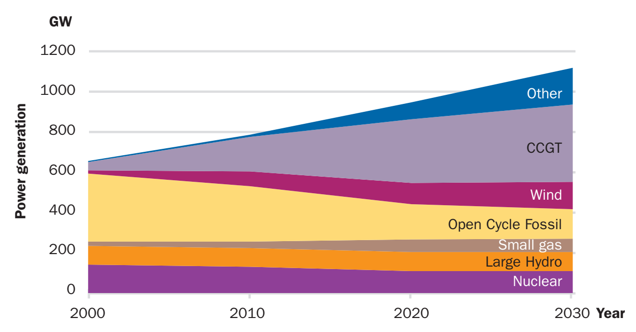
9 Institutional and legal issues

9.1 Background

According to the IEA[41] the EU will invest €100 billion in transmission networks and €340 billion in distribution networks for reinforcement, asset replacements and new connections over the three decades from 2001-2030. A dramatic increase in power consumption will require substantial investments in generation assets (see figure 39).

Figure 39: European Energy and Transport – Scenarios on key drivers, European Commission, September 2004



Source: European Commission

Consequently, it is clear that new investments in grids are needed to carry more electricity to European consumers. According to the European Commission, total installed power generation capacity will increase by more than 450 GW. A proportion of the increase in capacity will be wind power and grids will certainly be needed to carry that power.

Energy has been an integral part of European co-operation since the 1950s. Two of the three founding Treaties focus on the promotion of particular energy sources: the European Coal and Steel Community (ECSC), signed in 1951, and the Euratom Treaty (ET), signed in Rome on 25 March 1957, together with the Treaty Establishing the European Economic Community (EEC). The ECSC came into force in 1952 with a fifty-year operational life to promote and protect the use of coal. The Euratom Treaty has been in force since 1958 and has no expiry date.

Before the 1980s, electricity generation, distribution, enforcement, grid expansion and selling were undertaken by national, vertically-integrated monopolies that were granted exclusive rights. In the 1990s, the European Commission challenged the existence of such monopolies as being contrary to the Treaty's rules on the free movement of goods. This eventually resulted in the adoption in 1996 of the first electricity Directive and the first Directive on gas in 1998.

Following the adoption of the 1997 Treaty of Amsterdam, the European Union bases its energy policy on three core principles, namely[42]:

- **Environmental protection** – which is integrated in both energy production and energy use to maintain ecological and geophysical balances in nature.
- **Security of Supply** – which aims to minimise risks and impacts of possible supply disruption.
- **Competitive energy systems** - to ensure low cost energy for producers and consumers.

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[41] World Energy Investment Outlook, IEA 2003

[42] Energy in Europe, Economic Foundations for Energy Policy, The Shared Analysis Project, December 1999, European Commission, ISBN 92-828-7529-6, page 8.

9.2 Grids and market dominance: main barriers to competition

Since 2001, the Commission has monitored the development of market opening through the Benchmarking Reports on the Implementation of the Internal Electricity and Gas Markets. One of the most important conclusions of both the first and the second Benchmarking reports was that the way market opening is undertaken in the Member States was leading to significant distortions of competition, a lack of a 'level playing field' between companies from different countries of origin, and that this patchwork approach was failing to lead to the development of a competitive, integrated internal market[43].

A third Benchmarking report[44] was published by the European Commission in March 2004. Its conclusions on the outlook for future effective competition in electricity are similar:

"It is becoming clear that the main problem for electricity in the coming years will be the issue of market dominance at national level and the inadequate level of interconnection between Member States."

The status is even worse when it comes to gas, according to the Commission: *"Competition in the gas sector remains somewhat behind than that for electricity. A key barrier is the continuing dominance of the existing companies in their Member State or, in some cases, specific region."*

As a result of continued distortions to competition in electricity and gas, two new Directives on common rules for the Internal Electricity and Gas markets[45], known as the Second Liberalisation Package, was adopted and entered into force in 2003.

In its fourth Benchmarking report, published in January 2005[46], the European Commission warns that governments must do more to open up electricity and gas markets. The Commission points out four key reasons for the lack of success in achieving a competitive market:

- Lack of cross-border transmission links,
- Existence of dominant, integrated power companies,
- Biased grid operators, and
- The non-existence of liquid wholesale electricity markets.

From the European Commission's point of view the electricity grid and the structure of the power sector are the main stumbling blocks to effective competition in the European electricity markets. It sees market concentration and dominant incumbents as "the most important obstacle to the development of vigorous competition".

Further, it notes that *"the internal energy market will need to develop in a manner consistent with the Community's sustainability objectives. This means that the necessary incentives to support the penetration of renewables, the reduction of emissions and demand management need to be maintained."*

According to the Gas and Electricity Directives, from 1 July 2004 all business consumers and from 1 July 2007 all household consumers should be free to choose their supplier of electricity. However, Member States' track record in transposing the Directives has been rather poor. As a consequence, the European Commission announced on 13 October 2004 that it has commenced infringement proceedings against 18 out of 25 Member States that have failed to correctly transpose the Second Liberalisation Package.

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[43] "EU Energy Law, vol. 1, The Internal Energy Market"; Christopher W. Jones, 2004; ISBN 90 776 4401 6.

[44] Third Benchmarking Report on the implementation of the internal electricity and gas market; European Commission; 1 March 2004.

[45] Directive 2003/54/EC of the European Parliament and the Council of 26 June 2003 concerning common rules for the internal electricity market; Official Journal L 176, 15/07/2003 and Directive 2003/55/EC of the European Parliament and the Council of 26 June 2003 concerning common rules for the internal gas market; Official Journal L 176, 15/07/2003

[46] COM(2004) 863 final

The lack of effective competition in the electricity and gas markets is also noted by the Directorate General for Competition. As one of his last duties as EU Commissioner for Competition, Mario Monti took stock of the state of power and gas competition in a speech on 21 September 2004[47]. His verdict: *"the current level of competition is not encouraging".*

"In most national markets, customer switching rates are modest, substantial barriers remain for new entrants, market structures are highly concentrated and, last but not least, a single European energy market has not been achieved," Mr. Monti said. Commissioner Monti in particular warned against falling into the trap of too prudent an antitrust policy because of overestimation of the security of supply arguments that utilities use when justifying the ongoing vertical integration of the sector. In the past years, large energy companies have reduced their risks by participating in upstream projects such as gas exploration and by binding downstream customers through long term contracts on the provision of electricity. *"Such practices (…) lead to foreclosure and rigidity in the market, thereby endangering the liberalisation process."*

The main goal of introducing EU legislation to liberalise electricity and gas markets was to increase competition in the different areas of the sector and to create a level playing field between generators. Although market liberalisation is expected to give all consumers the ability to choose their energy supplier by mid 2007 and while the number of consumers that are free to choose their supplier increases, there is considerable doubt as to whether the market opening will also lead to a real choice of supplier. Giving consumers the freedom to choose a supplier does not necessarily guarantee effective competition. 90 years ago, Mr. Henry Ford allowed the American consumer to "have his car painted any colour that he wanted so long as it was black". Europe must escape a similar situation in electricity and gas where consumers continue to be free to choose any supplier they want as long as it is the incumbent monopoly.

In all but five of the 25 Member States the three largest utilities own above two thirds of the electricity generation capacity[48]. The figures even understate concentration as they do not take into account a very high degree of cross ownership, e.g. in Germany and Italy. The level of dominance is increasing as rules and practises continue to support the incumbent European generators and technologies and are encouraged by some Member States as utilities are built up to become national champions or are becoming part of a handful of European utility oligopolies.

■ Electricity market reform

Essential reforms in the electricity sector are necessary if new renewable energy technologies are to be accepted at a larger scale. Current energy legislation on planning, certification and grid access has been built around the existence of large centralised power plants, including extensive licensing requirements and specifications for access to the grid. This favours existing large scale electricity production and represents a significant market barrier to renewables. Furthermore it does not recognise the value of not having to transport decentralised power generation over long distances.

Distortions in the conventional power market include, for example: institutional and legal barriers; existence of regional and national dominant players; potential for abuse of dominant positions; barriers to third party access; limited interconnection between regional and national markets; discriminatory tariffs; no effective unbundling of production and transmission. One big challenge is to make the necessary redesigns of the grid infrastructure, system management, grid regulation and grid codes that reflect the characteristics of renewable energy technologies. Cross-border electricity interconnectors are also vital for those markets that are not geographically isolated.

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[47] Mario Monti Keynote Speech Energy Day; Energy Liberalisation: moving towards real market opening; 21 October 2004

[48] Third Benchmarking Report on the implementation of the internal electricity and gas market; European Commission; 1 March 2004.

The reforms needed to address market barriers to renewables include:

- Streamlined and uniform planning procedures and permitting systems and integrated least cost network planning;
- Access to the grid at fair, transparent prices and removal of discriminatory access and transmission tariffs;
- Fair and transparent pricing for power throughout a network, with recognition and remuneration for the benefits of embedded generation;
- Unbundling of utilities into separate generation and distribution companies;
- The costs of grid infrastructure development and reinforcement must be carried by the grid management authority rather than individual renewable energy projects;
- Disclosure of fuel mix and environmental impact to end users to enable consumers to make an informed choice of power source.

In addition to market barriers there are also market distortions which block the expansion of renewable energy. These distortions are in the form of direct and indirect subsidies, and the social cost of externalities, currently excluded from costs of electricity production.

A major barrier preventing wind power from reaching its full potential is the fundamental lack of pricing structures in the energy markets that reflect the full costs to society of producing energy.

Furthermore, the overall electricity market framework is very different today from the one that existed when coal, gas, and nuclear technologies were introduced. For most of a century, power generation has been characterized by national monopolies with mandates to finance investments in new production capacity through state subsidies and/or levies on electricity bills. As many countries are moving in the direction of more liberalised electricity markets, those options are no longer available, which put new generating technologies, such as wind power, at a competitive disadvantage relative to existing technologies.

Subsidies to fully competitive and polluting technologies are highly unproductive, seriously distort markets and increase the need to support renewables. Removing subsidies to conventional electricity would not only save taxpayers' money and reduce current market distortions in the electricity market. It would also dramatically reduce the need for renewables support. Wind power would not need special provisions if markets were not distorted by the fact that it is still virtually free for electricity producers to pollute.

Subsidies artificially reduce the price of power, keep renewables out of the market place, and prop up increasingly uncompetitive technologies and fuels. Eliminating direct and indirect subsidies to fossil fuels and nuclear power would help move us toward a level playing field across the energy sector.

Conventional energy sources receive an estimated $250-300 billion in subsidies per year worldwide, and therefore markets are heavily distorted. The UNDP World Energy Assessment in 2004 stated that in the mid-1990s governments worldwide were subsidizing fossil fuel and nuclear power by around $250-300 billion. A recent assessment of global annual energy subsidies in 1995-1998 put the total at $244 billion, of which 3.7% was for renewables. In 1997, the World Bank estimated that annual fossil fuel subsidies were $58 billion in the OECD and the 20 biggest countries outside the OECD.

R&D funding can make the crucial difference as to whether a technology becomes commercially viable, particularly at the early stage of development. It also accounts for about 40% of continued cost reductions in the technology. Over the last three decades 92% of all R&D funding – ($267 billion) has been spent on non renewables, largely fossil fuel and nuclear technologies, compared to 8% ($23 billion) for all renewable technologies.

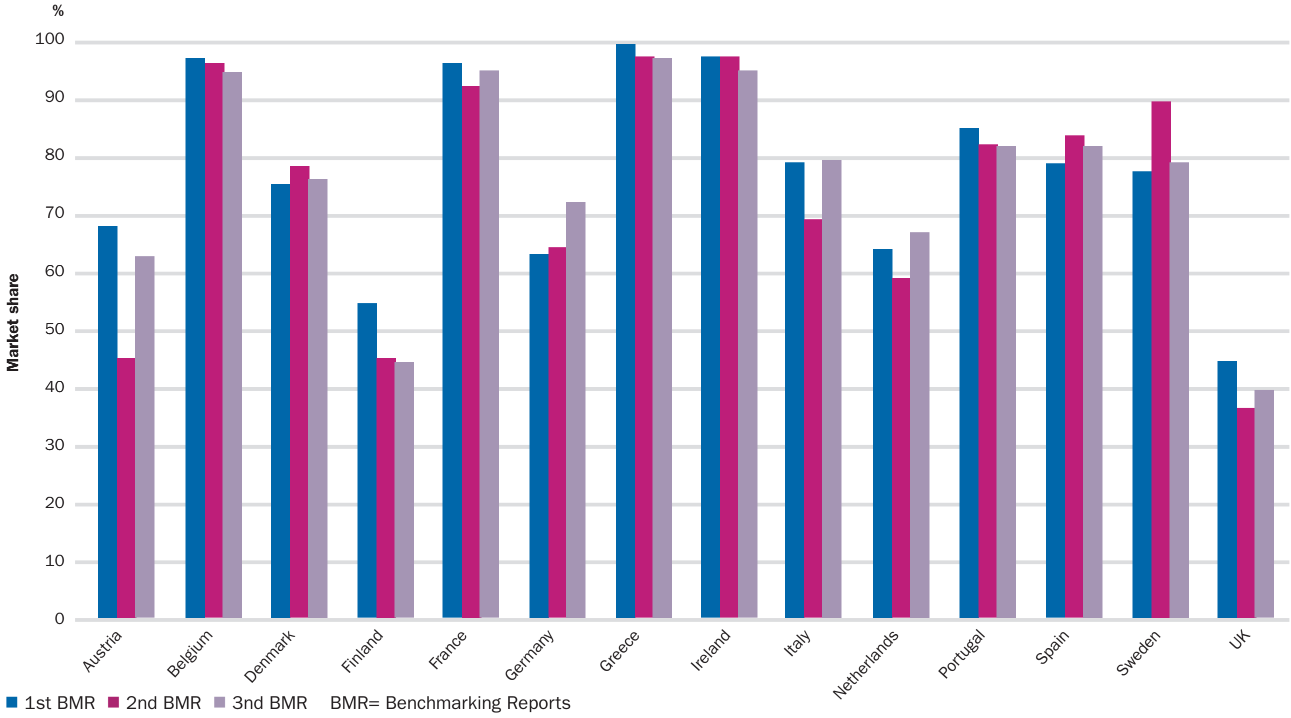
9.3 Dominant players

The European grid infrastructure is key to creating competition in European power markets. As the grids, in many European countries, are still an integral part of large vertically-integrated companies, the entire structure of the power industry has a direct effect on the future possibilities of connecting wind power, other renewables and other third party power generators to the European grids.

Market concentration continues to be one of the main barriers to effective competition in the European power markets. Analysis of merger and acquisition activity in recent years further suggests that the problem has been increasing throughout the liberalisation process. In EU-15 in the past years, the percentage share of the three largest generators in Member States has increased.

In addition the ownership of grids by utilities (vertical integration) continues. It gives vertically-integrated utilities a competitive advantage over other generation companies, especially new entrants to the market. In 12 of the Member States surveyed in the European Commission's Benchmarking report, the top three utilities control more than two thirds of the market. Furthermore, and of far greater concern, the average share of the generation market of the three largest utilities in each Member State is now 76%, up from the previous benchmarking report analysis of 73%[49].

Figure 40: Percentage share of market of three largest electricity generators



Source: European Commission Benchmarking Reports

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[49] DG TREN Draft Working Paper Third benchmarking report on the implementation of the internal electricity and gas market, Commission of The European Communities, Brussels, 01.03.2004

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Moreover, as stressed by Commissioner for Competition Mr. Mario Monti[50], from a competition perspective, power and gas markets are unlike other sectors. *"Market power can already be present where parties have market shares which would not be problematic in other sectors of the economy. (…) These markets [power and gas, ed.] indeed have a particular structure which facilitates both collusive behaviour and the exercise of market power".*

In other words, due to the specific nature of the power market, concentration becomes a barrier to effective competition at lower concentration levels than for other sectors in the economy.

The increasing national market share of the major utilities is driven by a larger trend of the concentration of the European market as a whole, whereby large private and State owned utilities are acquiring other companies across a whole range of utility services and thus the creation of vertically-integrated utility oligopolies. Large mergers of gas and power companies are also emerging. Although the rate of international mergers and acquisitions in the European energy market slowed in 2002 and 2003, there is still considerable activity. Between 2000-2003 the seven major European utilities – Electricité de France, Eon, RWE, Vattenfall, Enel, Endesa, Suez/Electrabel, invested €80 billion in mergers and acquisitions in Europe[51].

The increased dominance of these large pan-European vertically-integrated companies is also increasing the desire by Governments to establish and maintain 'national champions', which are larger national utilities developed to fend off takeovers. In Austria, Verbund, which controls half of the country's generation capacity, along with the five provincial generating companies, is protected through the Constitutional Act of 1947, which requires 51% State ownership in these companies and thus increased political control. This protection has to date included the protection of the domestic market from foreign competitors[52]. In recent years, the most notable example of building up a national champion is the merger of Eon and Ruhrgas in Germany, which was approved by the German Government in July 2002. This €10.4 billion merger was approved by the Ministry of Economics on 'national champion' grounds against the advice of the Federal German Cartel Office[53].

The European Commission has recognised the problems that market concentration is causing and will submit a report in 2005 on the current shortcoming in the market and may have to consider further measures 'if these drawback, notably the maintenance of dominant positions and non-competitive structures is not removed[54]'. To date, the main mechanism put forward by the European Commission and Council to address market concentration is to introduce measures to increase electricity flow between countries and specifically a requirement that the volume of interconnection capacity equates to 10% of the installed production capacity by 2005. By increasing interconnection, the dominance of national champions can be reduced and further competition can be introduced by electricity import. Unfortunately, the Member States are reluctant to support the measures put forward by the Commission. Another approach aired by the Commission is to force large utilities to sell off some of their generation capacity[55].

A specific threat associated with the development of ever-larger power oligopolies is the constant demand for electricity, coupled with the cost and complexity of its storage, making the market particularly susceptible to price manipulation. Consequently, there are fears that the increasing influence of these larger utilities in the market may continue to impact upon electricity prices and the creation of a level playing field between generators.

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[50] Mario Monti Keynote Speech Energy Day "Energy Liberalisation: moving towards real market opening"; 21 October 2004

[51] 2002 Results of the Electricité de France Group, March 2003

[52] Austria's Liberalisation experiment: a mixed bad. Alexander Samide and Klára Székffy, Raiffeisen Investment. European Electricity Review 2004, Platts

[53] Global Energy Regulation, Nera Consulting, July 2002. http://www.nera.com

[54] Ibid

[55] In praise of enforced plant divestment. John Bower, Senior Research Fellow, Oxford Institute for Energy Studies, Platts, European Electricity Review 2003

9.4 Third party access

Third party access to the grid is a precondition for creating a level playing field and real competition in the power markets. The continued high levels of market concentration in the power sector, and the distortions to competition must, until alleviated, be compensated for by fair, extremely transparent and coherent rules for third party access, that take into account the nature of the technologies.

One of the objectives of the original EU legislation on electricity market liberalisation was that the rules for introducing new generating capacity should be based on "objective, transparent and non-discriminatory criteria".[56] However, it was recognised when revising the Directive in 2001 that "important shortcomings and possibilities for improving the functioning of the market remain, notably in ensuring a level playing field in generation"[57].

For renewables, the only challenger ever to have made inroads into the monopoly power market, "objective, transparent and non-discriminatory criteria" are lacking in all but a few Member States. The small inroads that wind power has made into a few European power markets over the past two decades can be expanded upon and replicated by other new renewable technologies. But it requires that the existing frameworks and market rules, favouring incumbent generators and technologies, are changed.

The entire European infrastructure, as well as investments in capacity, were charged directly to electricity consumers by monopolies and depreciated over a few years. That gives new entrants and technologies a competitive disadvantage. New renewable investments have to compete with existing generators that have already been depreciated and paid for by European tax-payers and consumers. New entry into the power market is thus impeded by the obvious fact that it is cheaper to shovel more coal into an existing power plant than to build a new wind turbine.

As a result of the historic development of the power sector, infrastructure in the form of gas and electricity grids never had to be included in the project costs of new capacity. But the infrastructure is now owned by the incumbent oligopolies that have a large potential for benefiting economically from cross-subsidies. Due to the structural changes, as a result of liberalisation, new renewable energy plant in many Member States have to pay for new infrastructure and finance these through project costs – a situation unprecedented in the European power history. This, regardless of the fact that new grids benefit not only renewables but the entire operation of the infrastructure.

The Electricity Market Directive requires that the economic advantages of generation that are connected directly to the low voltage distribution grid be recognised. However, in a number of areas, additional costs can and are placed on renewable energy and other distributed generators. This includes lack of appropriate and transparent network charges, disproportionally high balancing payments and disproportionately high administrative charges, especially given the size of facilities.

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[56] Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity Official Journal L 027, 30/01/1997 P. 0020 – 0029, Article 4.

[57] Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC - Statements made with regard to decommissioning and waste management activities Official Journal L 176, 15/07/2003 P. 0037 – 0056, Recital 2.

9.5 Unbundling

The revised Electricity Market Directive adopted by Member States in July 2004, requires legal unbundling of the vertically-integrated utilities. However, it was not possible for Member States to agree on full ownership unbundling, leaving new entrants at the mercy of its oligopoly competitor and stifle competition and innovation.

Utilities are investing heavily in takeovers to vertically integrate. Analysis from Price Waterhouse Coopers suggests that vertical integration was the largest single motivating factor in the top forty global mergers and acquisitions in the energy sector in 2003[58]. The revised Electricity Market Directive has increased the separation between parts of the electricity industry, as it now requires legal separation between the Transmission System and Distribution System Operators from generation and supply activities. However, this unbundling requirement seems inadequate, and six Member States have actually opted for separate ownership requirements for TSOs.

There is some evidence already that increased unbundling goes hand in hand with increased competition between generators. In those countries with a requirement for ownership unbundling, the market share for generation of the three largest utilities is 66%, while in the remaining Member States, those with legal or management unbundling, the share is 84%. In addition to vertical integration with grid operators, re-integration of utilities is occurring between generation and supply companies. In recent years this trend has been particularly clear in Austria and the UK.

Another major source of distortion in the European power market is (dys)functioning of the wholesale power market as pointed out by IFIEC Europe[59]:

"As the consolidation of the electricity supply industry has intensified, only a small number of players remain and, together, constitute a de facto oligopoly. As trading on the wholesale market has been taken over by the powerful incumbents themselves, independent traders have abandoned Europe.

Managerial unbundling between the TSOs and their parent companies controlling generation and supply has not materialized in most Member States. This is one reason why access to the grid is still not *possible under reasonable economic conditions."*

Based on observations from large energy consumers, the IFIEC Europe concludes that many power producers refuse to negotiate prices. Instead they impose offers based on prices resulting from transactions on the wholesale trading markets – markets that are themselves fully dominated by the trading arms of the same power producers. Unlike the case for traditional commodity markets, the trading departments of the big electricity producers are the major players on both sides of the wholesale market: purchase and sales, since they act simultaneously as purchasers on behalf of the consumer and as sellers of their own production. The electricity price has become disconnected from fundamentals such as cost variations of primary fuel, significant shifts in demand/supply balance, etc. In addition, independent power traders have abandoned Europe, claims the IFIEC.

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[58] Power Deals 2003 Annual Report: Mergers and Acquisitions Activities within the Global Electricity and Gas Market, Price Waterhouse Coopers

[59] An analysis of the current dysfunction of the wholesale market in major parts of EU. IFIEC Europe, 29 september 2004.

9.6 Conclusions

Since 2001, the Commission has monitored the development of market opening through the Benchmarking Reports on the Implementation of the Internal Electricity and Gas Markets. In its fourth Benchmarking report, published in January 2005[60], the European Commission warns that governments must do more to open up electricity and gas markets. The Commission points out four key reasons for the lack of success in achieving a competitive market:

- Lack of cross-border transmission links,
- Existence of dominant, integrated power companies
- Biased grid operators, and
- The non-existence of liquid wholesale electricity markets

From the European Commission's point of view, the electricity grid and the structure of the power sector are the main stumbling blocks to effective competition in the European electricity markets. It sees market concentration and dominant incumbents as *"the most important obstacle to the development of vigorous competition"*.

Further, it notes that: *"The internal energy market will need to develop in a manner consistent with the Community's sustainability objectives. This means that the necessary incentives to support the penetration of renewables, the reduction of emissions and demand management need to be maintained."*

The four main barriers - i) lack of cross-border transmission links, ii) the existence of dominant, integrated power companies, iii) biased grid operators, and iv) the non-existence of liquid wholesale electricity markets – are not only barriers to creating effective competition in European power markets, they are also the main institutional and structural deficiencies preventing wind power and other new technologies to enter the market.

Cross-border transmission is a precondition for effective competition. It will also reduce the cost of integrating wind power on a large scale dramatically and reap substantial "geographic spread" benefits of variable output wind generation.

Electricity grids are natural monopolies and, hence, transmission and distribution must be effectively, i.e. legally and ownership-wise, separated from electricity production and electricity trading. The current structure leads to biased grid operators in many countries that are more concerned with optimising profits for their affiliated power producers and traders than to find the most cost-effective solutions to operate and extend the grids and give third-party access to new technologies.

Solving these historic structural inefficiencies in the European power sector will not only form the basis for real competition in the European power markets, it will also go a long way in removing grid barriers for wind power and other renewables and develop a European electricity supply system based on indigenous, clean, cheap and reliable technologies to the benefit of European consumers and the overall competitiveness of the Community. In order to solve current inefficiencies, possible actions include:

- Reduce market dominance and abuse of dominant positions
- Effective antitrust policies in the power sector
- Full legal and ownership unbundling between transmission/distribution, production and trading activities
- Improve cross-border interconnections between Member States
- Undistorted third party access to the grids at fair tariffs and removal of discriminatory practices

Adequate grid codes that reflect the nature of the technologies, developed in cooperation with industry and regulators should be developed and adopted.

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[60] COM (2004) 863 Final

10 General conclusions

Today less than 3% of Europe's power demand is being supplied by wind energy, but the potential contribution is five to ten times higher. This report has made an assessment of the various technical, economic and regulatory issues associated with large-scale integration. Europe's power systems have evolved around the utilisation of fossil and nuclear power plants. In view of security of supply, tightening environmental pressure and competitive energy prices, new and renewable energy sources such as wind power offer sustainable solutions for the power supply. Power systems have to adapt to enable an efficient use of these resources.

Technically, wind power is different from conventional fuel based generation by its variable-output characteristics, and by the decentralised location of the plants. This report provides arguments that a re-orientation in the European power systems to take these characteristics into account is technically and economically feasible, and in line with the European objectives.

The analysis of the technical integration issues in this report starts from an assessment of the variability characteristics of system-wide integrated wind power and from the technical 'grid-relevant' characteristics of wind power plants.

The major issues of wind power integration are related to changed approaches in operation of the power system, connection requirements for wind power plants to maintain a stable and reliable supply, extension and modification of the transmission infrastructure. In addition, cross-border links need augmenting to enable collection of wind power from onshore and offshore resources; this will also make best use of geographical aggregation. Finally, some institutional and legal barriers to increased wind power penetration need to be addressed. Conclusions on these issues are presented below.

System operation: power and energy balancing

Inherent capability of power systems to deal with wind power feed in

The possibilities and detailed strategies for managing significant wind power contributions vary between national and regional power systems. Like other form of power generation, wind power will have an impact on power system reserves. It will also contribute to a reduction in fuel usage and emissions. The magnitude of the impact of wind power in technical and economic terms depends mostly on the wind power penetration level. It also depends on the power system size, generation capacity mix, load variations, demand side manageability and degree of interconnection.

Large power systems can take advantage of the natural diversity of variable sources. A large geographical spread of wind power will reduce variability, increase predictability and decrease the occurrences of near zero or peak output. Power systems have flexible mechanisms to follow the varying load and plant outages that cannot always be accurately predicted. The same mechanisms are used to integrate wind power with its characteristic fluctuations. Wind farms have the inherent advantage over conventional power plants of being smaller in total output capacity. On the wind farm level, their power output variation is always smaller than, for example, the variation caused by an outage of a conventional plant. On regional aggregated level, wind power variations are smoothed and the occurrences of zero wind power are rare.

■ Not all variations of wind power output are significant for the power system

On the second to minute time scale wind power has very little if no impact on the reserves (primary reserve). This is because the large number of individual turbines will have their second-to-second variation uncorrelated and it will smooth out, together with the load variations.

Wind power variations on a time scale of 10… 30 minutes (intra-hour) will affect the secondary reserves in the system as the magnitude of wind power variations becomes comparable to load variations. The rare occasions when these variations are extreme (40% of wind power capacity) may be managed at critical times by wind farm operation and control procedures. At 10% penetration, extra (secondary) reserves corresponding to 2…4% of installed wind power capacity are needed, assuming proper use of forecasting techniques. The consensus from several national studies is that the corresponding extra cost for secondary reserves is quite low and amounts to €1-3/MWh (wind) at such wind power penetration level.

Wind power variations on a time scale of hours to days will affect the scheduling of conventional power plants (secondary and tertiary reserves) to an extent that depends on forecast 'efficiency' as well as on the flexibility of the conventional power producers in the system area. Minimising the unpredictable part of wind power using advanced forecast tools in combination with appropriate market rules helps to keep the additional system cost down to a low level. Efficient market rules in this respect should be applied to enable geographical and temporal aggregation of wind power, and to allow forecasts as close to real time as possible.

Accurate methods for short-term forecasting of wind power are widely available as there is a whole range of commercial tools and services in this area, covering a wide range of applications and customised implementation. All present, attained accuracy levels of output forecast methods for regionally aggregated wind farms are in the order of magnitude of 10% day ahead and 5% 1-4 hours ahead (RMS error on power output). On an annual basis, reducing the forecast horizon from day-ahead to a few hours ahead reduces the required balancing energy due to prediction errors by 50%.

Predictability favours the economic balancing of wind power in the system together with the fluctuations of electrical demand and other power generation sources, especially at wind power penetrations above 5%. The predictability qualities of wind energy must be analysed in a directly comparable way to that adopted for conventional plant which is not variable but is intermittent since large generating sets can be and are lost in an entirely unpredictable manner.

■ Additional options for managing increased wind energy feed-in

Beside balancing solutions using conventional generation units, other options for managing the increased variability seen by the power systems include load management, energy storage, interconnection and controllable wind power plants.

New technology and innovation enable wind farms of today to function as power plants (WEPP) with the capability of delivering a range of grid supporting services, such as frequency and voltage control. Whereas not necessary at low penetrations, these advanced wind farm properties will prove to be increasingly useful at high levels of wind power penetration.

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Connecting wind power to the grid

Grid codes

It is evident that clear rules are needed to ensure that the grid keeps operating well and safely when generators are connected. In this respect, wind energy technology is developing to keep up with ever stricter technical requirements.

Grid codes and other technical requirements should reflect the true technical needs and be developed in cooperation between TSOs, the wind energy sector and government bodies. Often grid codes contain very costly and challenging requirements (such as fault-ride through capability and primary control) that have no technical justification. They are often developed by vertically integrated power companies, i.e. within companies in competition with wind farm operators, in highly non-transparent manners. Furthermore, there are continuous changes of grid codes, technical requirements and related regulation, often introduced at a very short notice and with minimum involvement of the wind power sector.

The technical grid code requirements and regulations vary considerably from country to country. The differences in requirements, besides local 'traditional' practices are caused by different wind power penetrations and by different degrees of power network robustness. Wind turbine manufacturers would prefer less diversity of the regulations, although they are capable of complying with different regulations.

It has been suggested to introduce harmonised grid codes for wind energy at a European level. It could provide fewer burdens on the wind turbine manufacturers if each turbine model would not have to be adjusted for each market. However, it would be difficult to arrive at an all-encompassing European code for wind turbines because the technical requirements would have to reflect very different national conditions in terms of energy mix, interconnection, geographical size of the systems and wind power penetration levels. The immediate danger is that very strict requirements reflecting the technical needs in the few high wind penetration regions of Europe would be expanded to regions of Europe where such requirements have no technical justification and, thus, impose unnecessary cost on manufacturers as well as consumers in most European countries.

As a rule, the power system robustness and penetration level and other generation technology should be taken into account and an overall economically efficient solution should be sought. For example, it is more economic to provide primary and secondary control from conventional power plants, and wind farm operators should be demanded to provide such service only in cases where limits in existing reserves are foreseen for some critical situations. Moreover, the grid code requirement of participation in primary and secondary reserve is not suitable as a general provision since only recent wind turbine technology is capable to vary frequency response. Such a requirement could be in conflict with priority dispatching, attributed to 'non-programmable' renewable energy sources. For wind power, the priority in the dispatching can be considered to be much more relevant than participation in primary or secondary reserve. As for the fulfilment of the requirement for reactive power it could often be more economic to install and control devices such as FACTS directly in the transmission network.

Costly requirements should be included only if they are technically required for reliable and stable power system operation. The assessment of the need for requirements should be made by government bodies or TSOs that are fully separated from any generation activities, to avoid biased decisions. Wind turbine manufacturers are keen to establish a close working relationship with grid operators, customers and regulators to find acceptable compromises.

Beside the technical requirements, there is the issue of interconnection practice. There is a need for a transparent method to define the maximum interconnection capacity at a given network point as well as a definition of the maximum time for the TSO or DSO to perform relevant studies. Such method could ideally be defined by a neutral authority, for example a regulator.

■ Dynamic system studies provide basis for improved connection practices of wind power

In general, from dynamic system studies carried out for various countries (Denmark, Germany, Spain) it is concluded that power systems dynamics are not a principal obstacle to increasing the penetration of wind power, provided adequate measures are taken both in wind turbine technology and in the operation and technology of the grid. In particular, required technical measures for wind power plants as formulated in the grid codes are based on the results of these dynamic studies.

R&D should continue to further improve the knowledge on dynamic interaction of system and wind power plants. Also, continued research work is needed to improve the dynamic models for the latest wind turbine types and for entire wind farms. Such modelling efforts become increasingly important because several TSOs have started to demand that wind farm developers submit a dynamic simulation model of the wind farm before granting connection permits, in order to carry out dynamic grid integration assessments.

Upgraded transmission grid infrastructure needed

■ Upgraded grid infrastructure will benefit the whole power system

The European grid infrastructure needs upgrading – on country, cross-border and trans-European levels – not only to accommodate increasing amounts of wind power cost efficiently, but also other technologies. The IEA estimates that more than half of the new capacity required to meet rising electricity demand in the EU between 2001 and 2030 will be gas. It is very rarely part of the public debate how adequate transmission and distribution is secured for the large additions of gas and coal power plant in Europe over the coming decades.

The need for infrastructure investments is obviously not arising exclusively from an increased use of wind power, which seems to be the underlying message from many market participants. Consequently, grid extensions, grid reinforcement and increased backup capacity benefit all system users, not only wind power. Furthermore, it is impossible to allocate the cost to individual projects or technologies. Therefore it does not make sense to look at the future infrastructure challenges in the light of one single technology. It would be tantamount to making decisions on road building by only looking at the characteristics of bicycles, ignoring lorry and car traffic.

Wind power is not, and should not be, the only technology that benefits from improvements in the overall grid infrastructure and system operation. Therefore, an integrated approach to future decisions is needed which, of course should take into account the specifics of wind power technology as well as the specifics of other technologies.

Grid extensions and reinforcements will benefit the whole power system and is a precondition for creating real competition in the emerging EU internal electricity market – a challenge currently being blocked by numerous distortions in the conventional power market such as the lack of effective unbundling of transmission and generation companies. Grids are natural monopolies in nature and should be regulated as such, but this is presently not the case in most Member States.

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The process of upgrading the grid systems is very complex and requires short-term and long-term measures to enable a smooth integration of wind power. Short-term measures include mainly optimisation of existing infrastructure, and so-called soft measures like adapted management procedures. In the longer term, a European super grid is proposed to accommodate large amounts of offshore wind power and to utilize continental-wide smoothing effects of wind power to a maximal extent, as well as to improve the functioning of the emerging internal electricity market. The wind is always blowing somewhere, smoothening fluctuations, and enabling more accurate short-term forecasts. Grid upgrading entails the following categories of improvements:

- high-voltage transmission links between countries (e.g. through the ones established in the EU's TEN-E programme),
- offshore transmission links interconnecting different offshore wind farm areas and load centres over long distances,
- meshed long distance transmission infrastructures for interconnecting centres of load and generation on a European scale and beyond.

The TEN-E Guidelines acknowledge the integration of wind power into the European power systems as an additional driver for the development of European transmission infrastructures.

■ Cross-border transmission

Cross-border transmission of wind power appears to be less of a technical issue than a trade and market issue. The problems wind power is facing presently are mainly caused by the fact that there is not yet a slot of cross-border capacity for variable-output power from renewables. Making such slot available would enable cross-border trade in wind power according to the internal electricity market principles.

While the European RES-E directive requests priority dispatch for renewables to be implemented in the national regulatory frameworks, there is no such notion as priority allocation of cross-border capacity for electricity from renewables. According to the principles of the internal electricity market this allocation should be market-based, rather than historically determined.

■ Strategic grid planning

Planning of grid infrastructure and planning of wind power projects, now two independent processes, should be better coordinated, certainly on European level. The Trans European Networks for Energy (TEN-E) offer an appropriate vehicle to coordinate these two processes and to foster wind power integration, however at present the necessary funding is lacking. The TEN-E Guidelines clearly acknowledge the integration of wind power into the European power systems as an additional driver for the development of European transmission infrastructures. The guidelines should be improved to take necessary grid reinforcements as a consequence of future wind power developments into consideration. Studies need to be undertaken to investigate the transnational aspects of wind power integration and look for solutions on a European level to harmonise the various national grid integration efforts.

System adequacy and security of supply

Adding wind power to the existing system contributes favourably to the security of supply. Wind energy will replace energy produced by other power plants, which improves the energy adequacy of the power system. This is especially beneficial when wind is saving limited energy sources like hydro power and imported fuels like gas and oil, decreasing the effect of price peaks on the national economy.

Wind also contributes to security of supply and system adequacy by replacing conventional generating capacity. The effect of wind power on adequacy of power – in other words its capacity credit - will be limited. When wind power produces around 5% of the electricity consumption, its relative capacity credit is equal to the average wind power produced during times of peak demand (between 20% and 35% of installed wind power capacity, depending on the site conditions). At higher wind power penetration, its relative capacity credit becomes lower than the average wind power output in times of peak demand.

In addition to the above, adding wind power to the existing system is contributing favourably to security of supply by virtue of technology diversification and indigenous production.

Economic impacts of wind power integration

The economic impact of wind power integration is assessed by analysing the system costs and benefits of introducing wind power. Such analysis is performed on a national power system basis by comparing various scenarios with more or less wind power.

■ Consequences for reserves and additional balancing costs

Comprehensive national studies have focused on determining the additional balancing costs as a function of increasing wind penetration in the national power system (Nordic region, Germany, UK, Ireland, Spain). Despite the large spread in assumptions, optimisation criteria, system characteristics, the range of costs found in such studies is not very large. There is a gradual increase of the additional balancing costs with wind power penetration. Because of the positive effect of geographical smoothing, results from these studies show that power systems in large geographical areas can integrate wind power at lower cost. Likewise, good interconnection to neighbouring systems reduces balancing costs.

Both the allocation and the use of reserves cause extra system costs. This means that only the increased use of dedicated reserves, or increased part-load plant requirement, will cause extra costs. According to studies made so far, extra reserve needs estimated for wind power penetration can be drawn from the existing conventional power plants. Estimates regarding the costs of increase in secondary load following reserves suggest €1–3/MWh (of wind) for a wind power penetration of 10% of gross consumption and €2-4/MWh for higher penetration levels. The costs are quite sensitive to the accuracy of wind power forecasting, as well as the practice of applying forecasts in the market rules.

■ Additional network costs from national studies

A number of national studies (Austria, Denmark, Germany, France, Netherlands) have determined the additional grid reinforcement requirements and corresponding costs due to wind power. Such studies perform load flow simulations of the corresponding national transmission and distribution grids and take into account different scenarios of national wind integration, utilising the most favourable sites. These country-specific studies (both in view of onshore and offshore) indicate that the grid extension/reinforcement cost caused by additional wind generation are in the range of €0.1 to 4.7/MWh wind, the higher value corresponding to a wind penetration of 30% in the system (UK). When properly socialised in an unbundled market, these cost levels, as reflected in the end user price – even up to high wind penetrations - are quite low.

The allocation of changes of load flows in a system to a single new generator connected to the system (e.g. a new wind farm) is ambiguous, since established generators or changes in demand may cause an equal burden on the grid infrastructure. In general, all grid reinforcements will benefit the whole power system. A better interconnected European grid is also essential for creating real competition in the emerging Internal Electricity Market.

■ Overall system effects

Generation costs constitute the largest fraction of the cost of power. Expected cost developments of wind power and conventional generation are such that in a scenario with substantial amounts of wind power, the additional costs of wind power (higher installed costs, increased balancing, network upgrade) would be outweighed by the benefits. The expected continuing decrease of wind power generation costs (reduction of 20% for onshore and 40% offshore in 2020 as compared to 2003 levels) is an important factor. The economic benefit of wind becomes larger when social benefits of CO_2 emission reduction are taken into account.

Large national studies in UK, Germany and Denmark confirm that system integration costs, under the most conservative assumptions (gas price does not increase substantially, low to zero social benefit of CO2) are only a fraction of the actual consumer price of electricity and are in the order of magnitude of €0 to 4/MWh (consumer level). It is recommended that a similar study is undertaken at European level.

In addition, wind power by virtue of its relative price stability compared to fossil fuels, reduces portfolio generation costs. Wind and other zero fuel cost technologies therefore have a positive effect on the overall energy mix. Several studies have shown that when added to a risky, fossil-dominated generating portfolio, wind and other fixed-cost, zero fuel cost renewables reduce overall generating cost and risk.

There is an astonishing lack of interest from grid operators, conventional power producers and international institutions such as the IEA as well as from the European Commission to study the additional system costs (balancing requirements, grid extensions and reinforcements) for all other technologies than wind power. Such system costs come along with all electricity generating technologies, not only wind. Still, it is impossible to find any study on the system cost of other technologies than wind power. It must be a minimum requirement that similar studies are carried out for other technologies in order to make proper cost comparisons.

Institutional and legal issues of large scale wind power integration

Since 2001, the Commission has monitored the development of market opening through the Benchmarking Reports on the Implementation of the Internal Electricity and Gas Markets. In its fourth Benchmarking report, published in January 2005[61], the European Commission warns that governments must do more to open up electricity and gas markets. The Commission points out four key reasons for the lack of success in achieving a competitive market:

- Lack of cross-border transmission links,
- Existence of dominant, integrated power companies
- Biased grid operators, and
- The non-existence of liquid wholesale electricity markets.

From the European Commission's point of view, the electricity grid and the structure of the power sector are the main stumbling blocks to effective competition in the European electricity markets. It sees market concentration and dominant incumbents as "the most important obstacle to the development of vigorous competition".

Further, it notes that: "The internal energy market will need to develop in a manner consistent with the Community's sustainability objectives. This means that the necessary incentives to support the penetration of renewables, the reduction of emissions and demand management need to be maintained."

The four main barriers - i) lack of cross-border transmission links, ii) the existence of dominant, integrated power companies, iii) biased grid operators, and iv) the non-existence of liquid wholesale electricity markets – are not only barriers to creating effective competition in European power markets, they are also the main institutional and structural deficiencies preventing wind power and other new technologies to enter the market.

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[61] COM(2004) 863 final

Cross-border transmission is a precondition for effective competition. It will also reduce the cost of integrating wind power on a large scale dramatically and reap substantial "geographic spread" benefits of variable output wind generation.

Electricity grids are natural monopolies and, hence, transmission and distribution must be effectively, i.e. legally and ownership-wise, separated from electricity production and electricity trading. The current structure leads to biased grid operators in many countries that are more concerned with optimising profits for their affiliated power producers and traders than to find the most cost-effective solutions to operate and extend the grids and give third-party access to new technologies.

Solving these historically determined structural inefficiencies in the European power sector will not only form the basis for real competition in the European power markets, it will also go a long way in removing grid barriers for wind power and other renewables and develop a European electricity supply system based on indigenous, clean, cheap and reliable technologies to the benefit of European consumers and the overall competitiveness of the Community. In order to solve current inefficiencies, possible actions include :

- Reduce market dominance and abuse of dominant positions
- Effective antitrust policies in the power sector
- Full legal and ownership unbundling between transmission/distribution, production and trading activities
- Improve cross-border interconnections between Member States
- Undistorted third party access to the grids at fair tariffs and removal of discriminatory practices.

Adequate grid codes that reflect the nature of the technologies, developed in cooperation with industry and regulators should be developed and adopted.

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11 Glossary and definitions

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 (CIGRE definition) : a measure of the ability of the power system to supply the aggregate electric power and energy requirements of 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.

ANCILLARY SERVICES are Interconnected Operations Services identified as necessary to effect 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)

BLACK START CAPABILITY - Some power stations have the ability to start-up independently of a power grid. This is an essential prerequisite for system security as these plant can be called on during a blackout to repower the grid.

CAPACITY is the rated continuous load-carrying ability of generation, transmission, or other electrical equipment, expressed in megawatts (MW) for ACTIVE POWER or megavolt-amperes (MVA) for APPARENT POWER. (UCTE)

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

CONTINGENCY is the unexpected failure or outage of a system component, such as a generator, transmission line, circuit breaker, switch, or other electrical element. A **CONTINGENCY** also may include multiple components, which are related by situations leading to simultaneous component outages. (UCTE)

A **CONTROL AREA** is a coherent part of the UCTE INTERCONNECTED SYSTEM (usually coincident with the territory of a company, a country or a geographical area, physically demarcated by the position of points for measurement of the interchanged power and energy to the remaining interconnected network), operated by a single TSO, with physical loads and controllable generation units connected within the CONTROL AREA. A CONTROL AREA may be a coherent part of a CONTROL BLOCK that has its own subordinate control in the hierarchy of SECONDARY CONTROL. (UCTE)

A **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)

GATE CLOSURE: the point in time when generation and demand schedules are notified to the system operator.

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)

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)

Load-Frequency Control (LFC): See: SECONDARY CONTROL

Minute Reserve {15 Minute Reserve}: See: TERTIARY CONTROL RESERVE

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 busbar) 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.

The **NETWORK POWER FREQUENCY CHARACTERISTIC** defines the sensitivity, given in megawatts per Hertz (MW/Hz), usually associated with a (single) CONTROL AREA/BLOCK or the entire SYNCHRONOUS AREA, that relates the difference between scheduled and actual SYSTEM FREQUENCY to the amount of generation required to correct the power imbalance for that CONTROL AREA/BLOCK (or, vice versa, the stationary change of the SYSTEM FREQUENCY in case of a disturbance of the generation-load equilibrium in the CONTROL AREA without being connected to other CONTROL AREAS); it is not to be confused with the K-FACTOR. The NETWORK POWER FREQUENCY CHARACTERISTIC includes all active PRIMARY CONTROL and SELF-REGULATION OF LOAD and changes due to modifications in the generation pattern and the DEMAND. (UCTE)

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

POWER 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 {Frequency Control, Primary Frequency Control}

PRIMARY CONTROL maintains the balance between GENERATION and DEMAND in the network using turbine speed governors. PRIMARY CONTROL is an automatic decentralised 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.

The global **PRIMARY CONTROL** behaviour of an interconnection partner (CONTROL AREA/BLOCK), may be assessed by the calculation of the equivalent droop of the area (basically resulting from the DROOP OF ALL GENERATORS and the SELF-REGULATION OF THE TOTAL DEMAND). By the joint action of all interconnected undertakings, PRIMARY CONTROL ensures the operational reliability for the power system of the SYNCHRONOUS AREA. (UCTE)

PRIMARY CONTROL POWER is the power output of a GENERATION SET due to PRIMARY CONTROL. (UCTE)

The **PRIMARY CONTROL RANGE** is the range of adjustment of PRIMARY CONTROL POWER, within which PRIMARY CONTROLLERS can provide automatic control, in both directions, in response to a FREQUENCY DEVIATION. The concept of the PRIMARY CONTROL RANGE applies to each generator, each CONTROL AREA/BLOCK, and the entire SYNCHRONOUS AREA. (UCTE)

The **PRIMARY CONTROL RESERVE** 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)

The **PRIMARY CONTROLLER** is a decentralised/locally installed control equipment for a GENERATION SET to control the valves of the turbine based on the speed of the generator (for synchronous generators directly coupled to the electric SYSTEM FREQUENCY); see PRIMARY CONTROL. The insensitivity of the PRIMARY CONTROLLER is defined by the limit frequencies between which the controller does not respond. This concept applies to the complete primary controller-generator unit. A distinction is drawn between unintentional insensitivity associated with structural inaccuracies in the unit and a dead band set intentionally on the controller of a generator. (UCTE)

PX - The 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 centralised 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). In order to fulfil these functions, SECONDARY CONTROL operates by the NETWORK CHARACTERISTIC METHOD. SECONDARY CONTROL is applied to selected generator sets in the power plants comprising this control loop. SECONDARY CONTROL operates for periods of several minutes, and is therefore dissociated from PRIMARY CONTROL. This behaviour over time is associated with the PI (proportional-integral) characteristic of the SECONDARY CONTROLLER. (UCTE)

The **SECONDARY CONTROL RANGE** is the range of adjustment of the secondary control power, within which the SECONDARY CONTROLLER can operate automatically, in both directions at the time concerned, from the working point of the secondary control power. (UCTE)

The positive/negative SECONDARY CONTROL RESERVE is the part of the SECONDARY CONTROL RANGE between the working point and the maximum/minimum value. The portion of the SECONDARY CONTROL RANGE already activated at the working point is the SECONDARY CONTROL POWER. (UCTE)

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.

SMALL-SIGNAL STABILITY — The ability of the electric system to withstand small changes or disturbances without the loss of synchronism among the synchronous machines in the system while having a sufficient damping of system oscillations (sufficient margin to the border of stability).

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)

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.

A **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 optimisation of the network and generating system will not necessarily be complete after this time. (UCTE)

A **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)

MAIN CONCLUSIONS

1. System operation: power and energy balancing

- A large geographical spread of wind power will reduce variability, increase predictability and decrease the occurrences of near zero or peak output. Power systems have flexible mechanisms to follow the varying load and plant outages that cannot always be accurately predicted.
- Accurate methods for short-term forecasting of wind power are widely available as there is a whole range of commercial tools and services in this area. On an annual basis, reducing the forecast horizon from day-ahead to a few hours ahead reduces the required balancing energy due to prediction errors by 50%.

2. Grid connection: grid codes and excessive technical requirements

- Grid codes often contain very costly, challenging and continuously changing requirements and are developed in a highly non-transparent manner by vertically-integrated power companies, who are in direct competition with wind farm operators.
- Costly technical requirements should only be applied if there is a true technical rationale for them and if their introduction is required for reliable and stable power system operation. These are not needed at low wind power penetration levels.
- Power systems dynamics are not a principal obstacle to increasing the penetration of wind power.
- R&D should continue to further improve the knowledge on dynamic interaction of system and wind power plants.

3. Grid upgrades and costs are not an isolated wind power issue

- Grid extensions and reinforcements will benefit the whole power system and are a precondition for creating real competition in the emerging EU internal electricity market. Grids are natural monopolies and should be regulated as such.
- In the longer term, a European Super Grid is proposed to accommodate large amounts of offshore wind power and to utilize continental-wide smoothing effects of wind power to a maximal extent, as well as to improve the functioning of the emerging internal electricity market.
- Cross-border transmission of wind power is not a technical issue but a trade and market issue. Making slots available for renewable electricity would enable cross-border trade in wind power according to internal electricity market principles.

MAIN CONCLUSIONS

4. Fuel replacement and capacity credit of wind power benefit security of supply

- Wind energy will replace energy produced by other power plants, which improves the energy adequacy of the power system.
- Wind power replaces conventional generating capacity. The capacity credit of onshore wind power throughout Europe varies between 20% and 35% of the installed wind power capacity. High wind power load factors in peak demand season and good wind power exchange through interconnection have a positive effect on the capacity credit.
- Adding wind power to the existing system is contributing favourably to the security of supply by virtue of technology diversification and indigenous production.

5. The economic impacts of wind power integration are beneficial

- Additional balancing is very low and estimated at €1–3/MWh (of wind) for a wind power penetration of 10% of gross consumption and €2-4/MWh for higher penetration levels.
- The grid extension/reinforcement costs caused by additional wind generation are in the range of €0.1 to €4.7/MWh wind, the higher value corresponding to a wind penetration of 30% in the system (UK). When properly socialised in an unbundled market, these cost levels, as reflected in the end user price are low – even up to high wind penetrations.
- System integration costs, under the most conservative assumptions, are only a fraction of the actual consumer price of electricity and are in the order of magnitude of €0 to €4/MWh (consumer level).
- These additional costs of more wind power would be outweighed by the benefits from the expected continuing decrease of wind power generation costs - a reduction of 20% for onshore and 40% offshore by 2020 as compared to 2003 levels.
- The economic benefit of wind becomes even larger when the benefits of CO_2 emissions reduction and other environmental benefits are taken into account.
- Wind power reduces portfolio generation costs. When added to a risky, fossil-dominated generating portfolio, wind as a fixed cost zero fuel technology reduces overall generating cost and risk.
- Balancing costs, grid extensions and reinforcements come with all electricity generating technologies, not only with wind power. It is impossible to find any study on these system costs of other technologies than wind power, hence proper cost comparisons are not possible. Other parties should study and publish the additional system costs for all other technologies than wind power.
- Most countries and institutions continue to ignore the risk element of volatile fuel prices when making cost comparisons between different electricity generating technologies. Rather than using the commonly applied levelised cost approaches, it is recommended to adopt cost calculating methods allowing a proper economic interpretation of (easily quantifiable) cost and risk of volatile oil, gas and coal prices.

MAIN RECOMMENDATIONS

1. Improved system operation

- Imbalance payments and settlement on individual turbine level should always be avoided. It is the overall variability of output from all wind farms that is relevant to system operation.
- Long gate-closure times should be reduced for variable output technologies. There is no technical justification for having wind power predict future production 48 hours in advance as demanded by some grid operators. The shorter the gate-closure time for wind power is, the lower the overall cost to consumers.
- More effective balancing and settlement procedures that do not discriminate against variable output technologies must be introduced.
- Distribution grids must be more actively managed.
- Curtailment of electricity production should be managed according to least-cost principles from a complete-system point of view. As wind power is free, constraining of wind power should be the last solution and restricted to a minimum.
- The balance market rules must be adjusted to improve accuracy of forecasts and enable temporal and spatial aggregation of wind power output forecasts.
- Imbalances payments should be settled according to monthly net imbalances as established in e.g. California and Spain.

2. Fair and adequate grid connection requirements

- Grid codes and other technical requirements should reflect the true technical needs and be developed in cooperation between independent and unbiased TSOs, the wind energy sector and independent regulators.
- A European-wide grid code for wind power is not required.

3. Grid infrastructure investments

- A large geographical spread of wind power on a system should be encouraged through planning and payment mechanisms and the establishment of adequate interconnection. From a system and cost point of view, that will reduce variability, increase predictability and decrease or remove situations of near zero or peak output.
- The cost of grid extension should be socialised, as it is the case for all other electricity technologies. One reason to do it is that grids are natural monopolies.
- Grid connection charges should be fair and transparent and competition should be encouraged.
- In future developments of the European power systems, increased flexibility should be encouraged as a major design principle. Public private partnership and use of structural funds should play an important part.
- The benefits of distributed generation, e.g. reduced network losses and reduced need for grid reinforcements, must be recognised.

MAIN RECOMMENDATIONS

4. Proper credit to wind's contribution to system adequacy

- Proper, uniform standards for the determination of wind power's capacity credit must be developed. For small penetrations of wind power the capacity credit will be equal to the load factor in times of peak demand. For very high penetration levels, the capacity credit is reduced but never anywhere close to zero.
- European transmission system operators associations should – instead of referring to wind power as "non-usable power" recognise wind power's proper capacity credit.

5. Solving institutional inefficiencies and improve power market competition

Solutions include:

1. Reduction of market dominance and abuse of dominant positions
2. Effective competition policies and authorities in the power sector
3. Full legal and ownership unbundling between transmission/distribution, production and trading activities
4. Improvement and expansion of cross-border interconnections between Member States
5. Establishment of undistorted third party access to the grids at fair tariffs and removal of discriminatory practices
6. Adequate grid codes that reflect the nature of the technologies, developed in cooperation with the wind energy sector and regulators

- Electricity grids are natural monopolies and, hence, transmission and distribution must be effectively, i.e. legally and ownership-wise, separated from electricity production and electricity trading.
- The existing guidelines for trans-European energy networks (TEN-E Guidelines) can provide a good framework for upgrading the European grid infrastructure which has been characterised by underinvestment during the 1980s and 1990s.
- The nascent trans-national grids must be prepared to absorb offshore wind power, and the TEN-E can provide a vehicle to focus on this area.
- A European policy for offshore wind energy is needed. An Action Plan for offshore wind power that addresses offshore infrastructure would be an important step.
- A European "super-grid" should be developed to bring large amounts of offshore wind power to European consumers, similar to the way European gas pipelines have been constructed.

6. New and continued research and development efforts

Under the 7th EU Framework Programme for Research, more research is needed in the following areas:

1. Improved forecast methods
2. Methods for investigating dynamic interaction wind farms and power system
3. Transmission network studies on transnational level
4. Uniform methods for national system studies for balancing (reserve capacities and balancing costs)
5. Investigation of solutions to increase power system flexibility
6. Systematic output monitoring to validate theories on capacity credit

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About EWEA

EWEA is the voice of the wind industry - actively promoting the utilisation of wind power in Europe and worldwide.

EWEA members from over 40 countries include 250 companies, organisations, and research institutions. EWEA members include manufacturers covering 98% of the world wind power market, component suppliers, research institutes, national wind and renewables associations, developers, electricity providers, finance and insurance companies and consultants. This combined strength makes EWEA the world's largest renewable energy association.

The EWEA Secretariat is located in Brussels at the Renewable Energy House. The Secretariat co-ordinates international policy, communications, research, and analysis. It co-ordinates various European projects, hosts events and supports the needs of its members.

EWEA is a founding member of the European Renewable Energy Council (EREC), which groups the 6 key renewables industries and research associations under one roof.

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