Integrating Wind

Developing Europe’s power market for the large-scale integration of wind power

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Project Partners:
- Sintef Energiforskning AS
- Risø– DTU
- 3E
- Kema Nederland BV
- Technical Research Centre of Finland (VTT)
- Garrad Hassan and Partners Ltd
- Tractebel Engineering
- Deutsche Energie-Agentur (dena)

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TradeWind

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Contents

PRINCIPAL AUTHOR:
Frans Van Hulle, Technical Advisor to the
European Wind Energy Association (EWEA)

AUTHORS:
John Olav Tande, Sintef Energiforskning AS
Kjetil Uhlen, Sintef Energiforskning AS
Leif Warland, Sintef Energiforskning AS
Magnus Korpås, Sintef Energiforskning AS

Peter Meibom, Risø– DTU
Poul Sørensen, Risø– DTU
Poul Erik Morthorst, Risø– DTU
Nicolaos Cutululis, Risø– DTU
Gregor Giebel, Risø– DTU
Helge Larsen, Risø– DTU

Achim Woyte, 3E
Geert Dooms, 3E
Pierre-Antoine Mali, 3E
Alexandre Delwart, Windtest (formerly 3E)

Frits Verheij, Kema Nederland BV
Chris Kleinschmidt, Kema Nederland BV
Natalia Moldovan, Kema Nederland BV

Hannele Holttinen, Technical Research Centre of Finland (VTT)
Bettina Lemström, Technical Research Centre of Finland (VTT)
Sanna Uski-Joutsenvuo, Technical Research Centre of Finland (VTT)

Paul Gardner, Garrad Hassan and Partners Ltd
Greg van der Toorn, Garrad Hassan and Partners Ltd
James McLean, Garrad Hassan and Partners Ltd
Simon Cox, Garrad Hassan and Partners Ltd

Konrad Purchala, Tractebel Engineering
Sebastien Wagemans, Tractebel Engineering

Albrecht Tiedemann, Deutsche Energie-Agentur (dena)
Paul Kreutzkamp, Deutsche Energie-Agentur (dena)
Chanthira Srikandam, Deutsche Energie-Agentur (dena)
Jakob Völker, Deutsche Energie-Agentur (dena)

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FOREWORD

In 2008, more new wind energy capacity was installed in Europe than any other power generating technology, reaching a cumulative total of 64 GW. This demonstrates the growing recognition that wind energy is a low-risk, future-proof investment that creates jobs, generates technological leadership, enables greater energy independence and helps protect the climate. The Renewable Energy Directive, agreed in December 2008, establishes a 20% renewable energy target by 2020 for Europe, and the European Commission has suggested that 12% of the EU electricity demand needs to come from wind to meet this target, up from 4% in 2008.

However as the amount of wind energy in the electricity grid increases, new challenges emerge. Initially built for traditional power sources, the grid is not yet fully adapted to the foreseen levels of wind energy, and nor are the ways in which it is designed and operated. So far, adaptation has been slowed by planning and administrative barriers, lack of public acceptance, insufficient economic incentives for network operators and investors to undertake transmission projects of European interest, and a generally fragmented approach by the main stakeholders.

European grids need to be reinforced and better interconnected for higher system security and a more economical dispatch of power that ensures low wholesale electricity prices EU-wide. Moreover, when a greater amount of wind is added to the mix, the grid also needs to be able to guarantee an efficient transportation and exchange of power across national borders, so that the wind blowing in one spot, however remote or far offshore, can provide power far and wide. Grid reinforcement and an adapted power market design are essential if the EU's 2020 targets are to be met and surpassed.

The TradeWind project is the first EU-level study to explore the benefits a European grid with better interconnections and an improved power market design can have on the integration of large amounts of wind power. This report presents the project's findings. Looking ahead as far as 2030, it provides recommendations and guidelines for action at EU and national level to move towards a single European grid and power market that will enable more European citizens to benefit from wind power.

Arthorous Zervos
President, European Wind Energy Association

Frans Van Hulle
TradeWind Technical Project Coordinator

Source: EWEA /Winter

Executive Summary

Introduction

Europe's dependency on imported fossil fuel has become a threat to economic stability, increasing uncertainties over energy prices. At the same time, the European electricity industry is facing a huge challenge related to generation capacity investment needed in the coming years. The surplus capacity that existed in some countries prior to liberalisation is diminishing, and many existing power plants are getting closer to their decommissioning dates. For these reasons, one of the key points on the European energy policy agenda is to increase the share of the demand that is covered from renewable energy sources. European Commission targets related to reduction of greenhouse gases and energy dependency state that by 2020, 20% of all energy demand will be covered by renewables. The Commission estimates that approximately 34% of EU's electricity demand needs to come from renewables by 2020 (up from 16% in 2006) to meet the overall energy objective. It also envisages that wind energy will meet 12% of EU electricity demand by 2020, up from approximately 4% in 2008.

The renewable source of energy with the most potential for helping meet these targets is wind power. It is a very promising and mature renewable technology, using resources that are favourably distributed between Member States, both onshore and offshore. It is not only able to contribute to European energy independence and meeting the future climate goals, but it could also help to turn the serious energy security problem into a new opportunity for Europe providing economic benefit, employment, technology and research leadership.

The recent rapid growth in wind power generation, triggered by technological and industrial development and the move towards sustainable economics, indicates that wind power should be seen as one of the main domestic sources for electricity generation in the EU. However, with ever-increasing amounts of wind energy in the system, new challenges arise for the functioning of the interconnected grid, especially for balancing, security, planning, cross-border transmission and market design.

For an economic and efficient integration of large amounts of a variable output source like wind power, changes must be made to the design and operation of the power system for generation, transmission and distribution. When envisaging penetration levels of 20% of gross electric demand or more from wind energy, new directions need to be followed for both the design and operation of the power system and the electricity markets. Hence it is critical that the decision-making processes – for example, on grid reinforcements, technical standards, market rules and so on – are well thought through, resulting in consistent policy decisions.

Based on a single European grid and power market system, the TradeWind project explores to what extent large-scale wind power integration challenges could be addressed by reinforcing interconnections between Member States in Europe. Additionally, the project looks at the conditions required for a sound power market design that ensures a cost-effective integration of wind power at EU level.

In this way, the study addresses two issues of key importance for the future integration of renewable energy, namely the weak interconnectivity levels between control zones and the inflexibility and fragmented nature of the European power market. Work on critical transmission paths and interconnectors is slow for a variety of reasons including planning and administrative barriers, lack of public acceptance, insufficient economic incentives for TSOs, and the lack of a joint European approach by the key stakeholders.

At EU level, there are various political processes ongoing that involve grid improvements, such as the Third Liberalisation Package,(a) the Strategic Energy Technology Review,(b) the Commission Green Paper on European Energy Networks,(c) the development of a Blueprint for a North Sea offshore grid and the Priority Interconnection Plan.(d) Within these processes, the concept of a truly European transmission network and an efficient European power market that integrates large amounts of renewable energy needs to be backed up with recommendations based on technical and economic analysis – this is where TradeWind intends to contribute.

In order to analyse interconnection and power market rules in Europe, TradeWind simulated the power flow in the EU high voltage grid with a simplified DC flow based market model, representing the European power system as a single, perfectly functioning market. Development scenarios of distributed wind power capacity have been assumed – anchored at the years 2010, 2015, 2020 and 2030.

A Europe-wide wind model was used to look into the effects of possible grid dimensioning situations due to meteorological events, such as the passing of deep low pressure systems which are expected to cause large variations in wind power production and hence measurable changes in cross border flow. In parallel, main transmission bottlenecks have been identified, suggesting the most obvious network upgrades that would relieve existing structural congestion. The methodology allowed for the associated implementation costs as well as the effect on power flow to be quantified.

Equivalent network representations were used for the different synchronous zones: UCTE (all of Europe except the Nordic countries, GB and Ireland), Nordel (the Nordic countries), and GB and Ireland. Due to the limited amount of data the TradeWind Consortium had access to, especially for the UCTE area, intra-zonal transmission constraints were taken into account only to a limited extent, restricting cross-border flow mainly by individual tie-line capacities and net transfer capacity (NTC) values. To provide a degree of validation, the simulation results were compared with current

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(a) Commission of the European Communities, 2007.
Energising Europe – a real market with secure supply (third legislative package).
Available at http://ec.europa.eu/energy/gas_electricity/third_legislative_package_en.htm

(b) Commission of the European Communities, 2008. Second Strategic Energy Review - Securing our Energy Future.
Available at http://ec.europa.eu/energy/strategies/2008/2008_11_ser2_en.htm

(c) Commission of the European Communities, 2008.
Green Paper: Towards a Secure, Sustainable and Competitive European Energy Network. COM (2008)782.

(d) Commission of the European Communities, 2006.
Communication from the Commission to the Council and the European Parliament: Priority Interconnection Plan. COM (2006) 846.


Source: EWEA /Faulkner

cross-border exchanges and results from a more detailed recently obtained model, strengthening the confidence of the TradeWind Consortium in the results and conclusions drawn. The intention was not to make an in-depth grid dimensioning study nor to consider dynamic grid behaviour and reliability aspects such as N-1 considerations.

Beside the Europe-wide assessment of the transmission networks, TradeWind analysed the power market's efficiency in handling large amounts of wind power. For this purpose, two simulation tools – namely, PROSYM and the WILMAR Planning Tool – were used to analyse a number of fundamental scenarios defined by the installed wind power capacity, the electricity demand and the energy economic scenario for a given target year. The considered parameters are interconnector capacity values (NTC), market gate closure time (or deadline for rescheduling of dispatch decisions) and the extension of the overall market area. The TradeWind cost analysis focuses on the marginal operation costs and does not take into account investment costs, additional balancing costs and wind energy incentive schemes. The cost analysis should be considered in this perspective.

Main conclusions of the TradeWind study

TradeWind was the first study to look into large-scale cross-border wind power transmission and market design at European level. From the simulations and analysis performed, it draws the following conclusions.

IMPACTS OF INCREASING WIND POWER ON CROSS-BORDER POWER FLOWS

Increasing wind power capacity in Europe will inevitably lead to increased cross-border energy exchanges. This implies that the current cross-border transmission bottlenecks will get more severe. Especially with the amounts of wind power capacity expected in 2020 and 2030, congestion can be expected to increase on the borders of France, between GB and Ireland and on some of the Swedish, German and Greek borders. The fact that wind power cannot be predicted with 100% accuracy leads to deviations between the expected and actual cross-border power flows on most interconnectors during a substantial part of the time, and this will further exacerbate the congestions.

The economic consequence of these transmission constraints is restricted access to cheaper generation resources (such as wind power which has zero marginal production costs because the fuel is free) and consequently higher electricity prices. The diminishing transmission capacity margins can also lead to reliability issues. As such analysis is out of the scope of the project it has not been carried out by the TradeWind partners.

As far as meteorological events are concerned, cross-border transmission is not significantly affected by wind power fluctuations for most of the European countries for installed wind capacity scenarios up to 2015. Even if wind power plants are cut off due to a rare storm and a dramatic drop of production occurs in one country, the effect was not so much seen at a European scale. However, the TradeWind Consortium suggests that this issue be studied more closely with more precise and higher resolution wind data, especially at wind penetration levels of 10% and more. Due to its limited temporal resolution, the wind data used in the TradeWind project can lead to short-term local wind power variations being underestimated.

NECESSITY OF TRANSMISSION UPGRADE ONSHORE AND OFFSHORE

It is clear that the future transmission reinforcements currently planned by TSOs plans are insufficient to prevent bottlenecks being aggravated and to alleviate congestion. As a consequence, without transmission upgrades beyond those currently planned, even a moderate increase in wind capacity will cause unnecessarily high operational costs of power generation in 2020 and 2030.

Both wind energy and transmission system upgrades contribute to reducing these operational costs of power generation. It is therefore important to consider the combined benefits when investment costs together with additional costs for balancing, incentives and the like are brought to the picture.

TradeWind has identified 42 onshore interconnectors and a corresponding time schedule for upgrading that would benefit the European power system and its ability to integrate wind power. Reinforcing these lines should lead to substantial cost savings for power system operation. Especially for 2020 and 2030, the benefits of these transmission upgrades become significant and amount to savings in total system operation costs of 1,500 M€/year, justifying investments in the order of €20 billion.


Source: Iberdrola

An interlinked (meshed) offshore grid could link future offshore wind farms in the North Sea and the Baltic Sea and the onshore transmission grid. A preliminary economic analysis based on an installed wind power capacity of 120 GW shows this system compares favourably to a radial connection solution where wind plants are only connected directly to the onshore grid. Among the possible benefits are increased cable utilisation, better access to the flexible hydro capacity of Norway, greater flexibility for transporting offshore wind power to areas of high prices and improved power trade between Sweden, east Denmark and Germany. It is recommended to take account of necessary onshore reinforcements in a further analysis. This could not be done in the TradeWind project because of the limitations of the available network data.

In order to effectively integrate high amounts of offshore wind into the power system, it is necessary to further upgrade the onshore network. Highly congested mainland connections were observed internally in Germany and Sweden, and in interconnectors between Belgium and the Netherlands and between Belgium and France. In addition to further reinforcements of mainland connections in these areas beyond 2015, much stronger offshore "super" grids with direct extensions towards major load centres inland could be built. Such a supergrid should not be a substitute for the necessary reinforcements of the onshore grid that are in the pipeline or under construction.

Taking into account the reluctance among the stakeholders and the general public, and the long implementation periods normally associated with the reinforcement of transmission systems, it is important to utilise existing transmission lines to the maximum extent by implementing power flow control technologies.

The investments are largely to be made in the individual Member States for both wind energy and transmission. This makes it difficult for transmission system companies to identify profitable transmission development projects, especially cross-border projects. The European dimension of these transmission justifies an EU approach to developing financing schemes for pan-European transmission grid reinforcements. In parallel there is a pressing need for harmonised planning and authorisation processes (fully supporting the TEN-E and related processes).

EU-WIDE WIND POWER CONTRIBUTION TO SYSTEM ADEQUACY

As well as providing large amounts of electricity that would otherwise be generated by fuel-burning plants, wind power has the potential to replace conventional capacity at a high degree of reliability. Joining together, or 'aggregating' wind energy production from several countries strongly increases wind power's contribution to firm power capacity in the system. The larger the geographical area represented by the grouped countries, the higher the increase of the capacity credit. For 2020 and 200 GW of installed wind power capacity, the effect of aggregating wind energy across multiple countries almost doubles the average capacity credit compared with the capacity credit averaged over separate countries. With the probabilistic method, the capacity credit for 200 GW wind power rises to a level of 14% which corresponds approximately to 27 GW of firm generation capacity. Providing sufficient transmission capacity between Member States will help maximise this effect.

Source: Nordex

POWER MARKET DESIGN FOR HIGHER MARKET EFFICIENCY

The establishment of intra-day markets for cross-border trade is of key importance for market efficiency in Europe. Allowing for intra-day rescheduling of cross-border exchange will lead to savings in operational costs in the order of €1-2 billion per year compared to a situation where cross-border exchange must be scheduled day ahead. In order to ensure efficient interconnector allocation, they should be allocated directly to the market via implicit auction.

Intra-day rescheduling of the portfolio - that is, taking into account wind power forecasts up to three hours before delivery - results in a reduction in operational costs of power generation of €260 million per year (compared to day-ahead scheduling) thanks to the decrease in demand for additional system reserves. This cost reduction assumes a perfect market and would be higher under the current, distorted market conditions.

The European electricity market needs the following major design characteristics in order to enable effective and efficient wind power integration:

- Features for intra-day rescheduling of generators and trade on an international level for low system costs and stable prices
- Wide-spread application of implicit auctioning to allocate cross-border capacity (i.e. market coupling, market splitting and so on)
- The availability of sufficient interconnection capacity, especially after 2015

Recommendations of the TradeWind study

Based on the analysis of the simulation results, TradeWind has developed a series of recommendations. These are addressed to policy makers, TSOs, energy regulators, wind power producers and traders. The recommendations relate to:

- Necessary technical developments
- European-wide transmission planning
- Regulation in the electricity market
- National and EU policies
- Further studies

Most of the recommendations are valid for the short to medium term.

UPGRADING AND OPERATING THE TRANSMISSION NETWORK

The staged network reinforcements as considered by TradeWind should be further investigated and promoted as a priority because of expected increase in wind generation after 2015. Network planning and other measures should aim to relieve the expected congestions in 2020 and beyond due to a higher demand and installed wind power capacity. The most severe bottlenecks are expected to be located on borders between France and its neighbours (Spain, Switzerland, Belgium, GB); between GB and Ireland; between Germany and Sweden; between Sweden, Poland and Finland, and between Greece and Bulgaria.

The TradeWind study should be followed up with more detailed design and optimisation of offshore grid solutions. The initial assessment in TradeWind indicated that meshed offshore grids are the economically optimum means of interconnection and that HVDC meshed grid technologies would offer important advantages for this application. Therefore it is recommended that R&D efforts in meshed HVDC technologies are sped up to enable them to be implemented for network expansion in the North Sea. The TradeWind HVDC meshed grids are proposed for consideration as a basis for developing the EU Blueprint for an offshore North Sea Grid.

In order to effectively integrate high amounts of offshore wind into the power system, it is also necessary to further upgrade the onshore network. Highly congested mainland connections were observed internally in Germany and Sweden, and on interconnections between Belgium and the Netherlands and Belgium and France. In addition to further reinforcements of mainland connections in these areas beyond 2015 building much stronger offshore grids with direct extensions towards major load centres inland should be considered.

A very important conclusion of TradeWind analyses is that there is almost the same need for transmission system upgrades if very little new wind power capacity is installed. Even if we were not going to increase wind power substantially, European consumers would benefit economically from the upgrades and operational changes suggested here. Both wind energy and transmission system upgrades contribute to reducing these operational costs of the power system. It is therefore important to consider the combined benefits when investment costs and other additional costs related to wind power are assessed.

Source: Vestas

Financing schemes for pan-European transmission grid reinforcements should be developed at EU level, as well as harmonised planning (including spatial planning) and authorisation processes fully supporting the TEN-E and related processes.

Strategies for handling regional concentration of wind energy and moving storm fronts should be developed further in order to avoid any negative impact on the security of the system as a whole. These strategies should include a more intensive use of wind forecasting and the possibility for system operators to control wind generation in a critical situation where strictly necessary for safe system operation. In this way, they could reduce the rapid loss of wind generation caused by storm fronts to a more manageable gradient by reducing wind production in advance of the storm front.

Contractual arrangements ('grid codes', connection agreements and similar) should contain provisions for wind generation to be controlled by the system operator as this may in some circumstances be the best solution to specific problems. The means of allocating curtailment, and any compensation arrangements, should be transparent and equitable between different generating technologies.

All grid operators should have 'visibility' of the real-time output of all types of generation connected to their networks. Additionally, at least the summated output of generators connected to distribution systems operating below the transmission system operator (TSO) grid should be available for the TSOs (except perhaps the smallest generators connected at domestic level). The associated cost – for example, for communications and control means - is small in comparison to the benefits that could be provided to system operators.

POWER MARKET DESIGN

The power market design should allow intra-day rescheduling of international transmission lines. The establishment of cross-border intra-day markets is of key importance for market efficiency in Europe.

Further, to maximise the economic benefits from interconnections, its capacities should be allocated via implicit auctions, for example market coupling or splitting algorithms. Optimally, these algorithms should be flow based. Further market integration in Europe – such as the regional market initiatives – should be pursued.

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

An international exchange of reserves brings further advantages. The trade-off between savings in investments for flexible power plants and sharing of reserves across borders should be investigated with dedicated models.

WIND POWER GENERATION

For the large-scale deployment of offshore wind, the siting process should ensure as much geographical spreading as possible in order to minimise large wind power variations. For the same reason, offshore wind farms in large-scale deployment should be connected to meshed offshore grids, possibly with controllable power flow, rather than to single radial connections from individual wind farms to the shore.

The options of active wind power plant control should be further explored, both from a technical and a commercial point of view. In some load situations, such as low demand combined with high wind speeds, some of the wind power capacity might be more useful as a reserve than as realised generation, making use of current state-of-the art wind power plant controllers that enable the use of the wind power as reserve.

As long as the power market is operating differently from a perfect market, because of the constraints in cross border exchange amongst other reasons, priority access and dispatch for wind power should be regarded as a means of helping keep wholesale power prices low and meeting the European 20-20-20 targets.

OTHER FORMS OF POWER GENERATION

Wind power capacity credit should be assessed in TSO system planning (such as system adequacy forecast) in larger areas than a single country or balancing area, because its value increases with the size of the area. The methodology for estimating the capacity credit of wind power should be further developed and harmonised over Europe for use in system adequacy planning.

Energy efficiency measures in order to significantly reduce electricity demand are an essential complement to renewable energy, in order to prevent increase in demand offsetting the cost and CO_2 savings achievable through large-scale wind power.

The effect of demand-side measures such as electrical vehicles, cold storage, heat system integration and so on should be further investigated because of the expected system cost reductions in future systems with large-scale wind power. Moreover energy storage can help to avoid curtailment of wind power in situations of low demand combined with high wind energy generation.


Source: EWEA/Bris


Source: LM Glasfiber

EUROPEAN POWER SYSTEM STUDIES

For any further transmission studies on a European scale, the wind data developed for TradeWind can be used (geographically and time consistent set, with a temporal resolution of six hours). Linear interpolation of the six-hourly data into hourly values showed a high correlation with hourly measured data during validation checks of specific locations. It was possible to transform these data into hourly data by adding the hourly variability as found in historical hourly wind power series for use in the market models.

However, for studies of generation adequacy, balancing and similar issues, European wind data with better temporal resolution, ideally hourly, is recommended. Intervals shorter than this are not justified because the spatial averaging effect over large areas will have very little change on this sort of timescale.

The following parts of TradeWind's simulation toolbox should be further developed if used in European power system studies:

- Hourly measured wind data series
- More detailed data on conventional power generation
- The effect of energy efficiency measures and demand-side management on the integration of wind energy should be studied with more power demand scenarios
- More detailed geographical modelling of wind power capacities
- The effect of weather systems should be studied for higher wind power penetration levels and with more accurate data with higher resolution for short-term studies (say up to five years ahead): beyond that timescale, the uncertainties in wind generation installation rates and locations make more detailed geographical resolution unjustifiable
- Simulate the operation of power flow control options in the power system simulation tool to study possible related market benefits
- Further development and harmonisation of the methodology for wind power capacity credit estimation

In order to facilitate Europe-wide transmission studies, data on European networks for power system studies should be made more readily available.

Source: EWEA/Winter

1. **Introduction**

1.1 Context – background

European energy policy [1] foresees a large contribution from wind energy to European power generation, in the same order of magnitude as individual contributions from conventional technologies. Experiences in regions with high wind penetration for example in Denmark, Spain and Germany supported by national power system studies [2] demonstrate that this is technically and economically feasible, while maintaining a high degree of system security.

The European wind power industry has formulated targets of 180 GW in 2020 and 300 GW in 2030 [3]. Respectively, the two targets correspond to wind energy penetration levels of up to 14% and 28% of gross electricity demand, assuming successful increase in energy efficiency.[e]

Increasing wind energy penetration from the 2008 level of 4% to a more ambitious 20-30%, in accordance with European energy policy and global climate change requirements, is technically feasible. However, such an increase is likely to be slowed by regulatory, institutional and market barriers, especially related to international trading of energy in the time scale of some hours ahead (intra-day).

In some regions the net cost of power from wind energy falls within the range of costs of other mainstream forms of electricity generation. Significant barriers to achieving the EU-2020 levels are related to the timely provision of electrical network infrastructure to alleviate network congestions and to accommodate increasing power flows caused by increased international power exchange. Other barriers for effectively integrating wind power are related to present inefficiencies in power markets.

Fundamental to understanding the integration challenges is to consider wind power as a continental power source. The variability of wind power is a challenge. A basic characteristic of wind generation is the movement of large weather systems across Europe. The advantage lies in the fact that meteorologically wind speeds across Europe in distances corresponding to the scale of weather systems (1,000 km) are not well correlated, in otherwords: wind is always blowing somewhere. A well interconnected network is a precondition to make optimal use of this spatial de-correlation of wind power. Cross-border exchange of power enables the capture of the smoothening effect of geographical aggregation on the variations of wind power production, enable improved accuracy of wind power production forecasts, and increase the capacity credit of wind power.

Alongside an adequate transmission infrastructure it is also necessary to have market rules that allow for the operation of the system such that there is an efficient international power exchange. Market rules that have developed for conventional generating technologies, based on trade between large vertically-integrated power companies, are not necessarily efficient for wind and other renewable generation.

The TradeWind project was set up to analyse the impact of European wind power on cross border electricity flows in greater detail. It was then to formulate recommendations for grid upgrades and improved power market rules.

TRANSMISSION
In order to capture the benefits of wind power, the rules and methods governing the planning and operation of the transmission network need to be optimised to take account of large-scale distributed power production from wind farms and their locations. Moreover, in order to fully access the large offshore wind potential in the North Sea, an additional grid system offshore and reinforcements onshore are necessary.

Planning at European level, previously the responsibility of the system operators via the organisations ETSO and UCTE, is now being taken up by the recently established European Network for Transmission System Operators for Electricity (ENTSO-E). Furthermore, network planning process need to include the impact of wind power. TradeWind is focusing specifically on the cross-border flows with a time horizon until 2030.

MARKET
For an efficient integration of wind energy into the European energy supply, transmission capacity is essential but more is needed. Along with transmission lines, rules are required that lead to an efficient allocation of their capacity given the European generation mix of the future. In line with the liberalisation of power markets in Europe, these rules are preferably market-based. TradeWind is investigating the techno-economical basis for market rules that provide an incentive to the market parties for global minimisation of the power supply costs and CO_2 emissions of power supply, within the energy economic context in Europe as anticipated for 2020 and beyond.

1.2 Scope, objectives and method of the TradeWind project

The TradeWind study was carried out from November 2006 to December 2008 with the financial support of the European Commission through the Intelligent Energy Europe (IEE) programme.

The long-term objective of TradeWind is to facilitate the dismantling of barriers to the large-scale integration of wind into European power systems on transnational and European levels. It aims to formulate recommendations for policy development, market rules and interconnector allocation methods in order to remove unjustifiable barriers to wind power integration. The scoped area is the EU-27, and includes the transmission networks in the synchronous zones of UCTE, Nordel, GB and Ireland.

The time horizon of the study, which goes up to 2030, includes one short, medium and long term. The study makes snapshots for target years 2008 (present), 2010, 2015, 2020 and 2030. The 2015 case is chosen in order to enable comparisons with the EWIS study of the European TSOs.

Although TradeWind includes technical aspects and modelling, the emphasis is on regulatory, institutional and market aspects of wind integration. As such it is not the purpose to make an in-depth grid dimensioning study nor to consider dynamic grid behaviour and reliability aspects such as N-1 considerations.

The TradeWind analysis uses the simulation of cross-border power flows in European transmission systems using future wind power capacity scenarios, representations of present and future network configurations and simulation of market behaviour with different market rules. In this way, it can examine and quantify the effect of increasing wind power penetration on power flows in European grids. A range of wind power capacity scenarios up to 2030 are being used for the simulations, enabling trends in the results to be analysed.

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[e] The estimated wind energy production is 477 TWh in 2020 and 925 TWh in 2030.

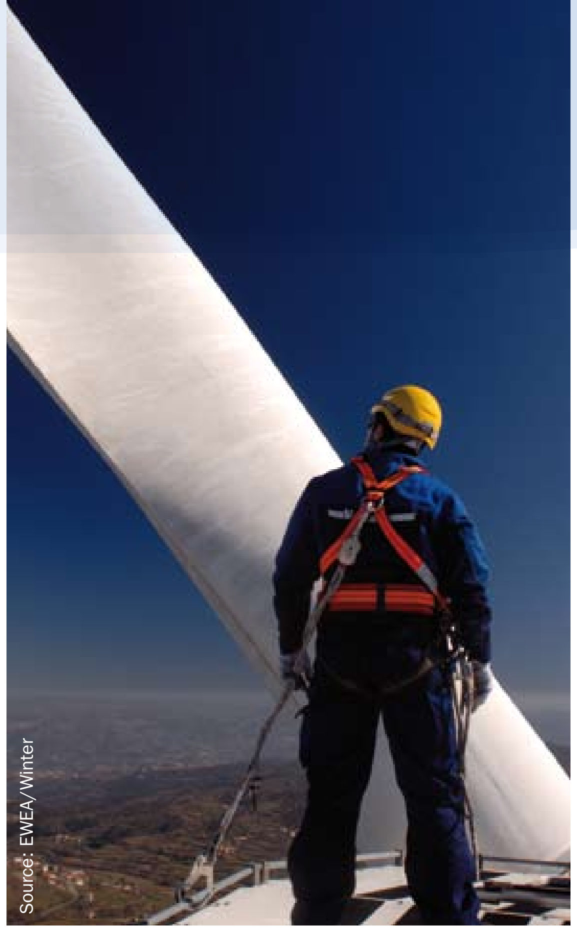
TradeWind recommendations build on the following elements:

- The effects of moving weather systems on cross-border flows in different wind penetration scenarios
- Accuracy of wind power forecasting at the international level
- Grid reinforcement scenarios
- European capacity credit of wind power
- Effect of improved market rules on power market efficiency

Other ways of improving the ability to integrate variable output renewables, such as the use of energy storage, have not been investigated in the project.

1.3 TradeWind project approach

The TradeWind project steps constituted the different project work packages:


Source: EWEA/Winter

Phase 1 Preparation		
WP2 (GH) Wind power scenarios	WP3 (Sintef) Grid modelling and power system data	WP4 (Risø- DTU) Identification of market rules
Phase 2 Simulation and analysis		
WP5 (VTT) Continental power flows	WP6 (Sintef) Grid scenarios	WP7 (3E) Analysis of market rules
Phase 3 Recommendations		
WP8 (EWEA) Recommendations for grid upgrade, market organisation and policy development		

TABLE [1]: **Project structure.**


Source: EWEA/Leeming

1.4 Stakeholders (TSOs, wind power industry, traders…)

TRADEWIND CONSORTIUM REPRESENTS STAKEHOLDERS

The TradeWind consortium represents, almost all of the crucial stakeholder groups, and throughout the project it has reached out to the remaining stakeholders. This is essential not only for the acquisition of data and a deepened understanding of stakeholder perspectives, but also to provide the greatest possible chance that the project findings are taken up by the sector and help to provide the basis for taking forward the integration of wind energy.

The TradeWind consortium is made up of:

1. Utility stakeholders represented by Tractebel, one of Europe's largest power engineering companies, and the leading consultancy on the transmission and distribution of electricity
2. Technical and policy research establishments, represented by VTT, SINTEF, and Risø National Laboratory
3. Member State energy agencies, represented by Dena
4. Leading consultancies in wind energy, energy policy and energy markets, represented by Kema, Garrad Hassan and 3E.
5. The wind energy industry itself and, in particular, project developers and wind turbine manufacturers, represented by the European Wind Energy Association (EWEA).

PROJECT ADVISORY BOARD

During the project period the Project Advisory Board provided feedback on method and results. Experts representing following companies, parties and consortia have taken part in the activities of the Advisory Board:

- TSOs: via the EWIS Consortium (European Wind Integration Study)
- European Commission: EACI and DG TREN
- Project developers/operators: Airtricity, Evelop, Acciona, WE@SEA
- Traders: EFET, BELPEX
- Experts in regulatory affairs: NEWES

TRANSMISSION SYSTEM OPERATORS

Transmission System Operators (TSOs) have been involved in the Advisory Board. A common Working Group was set up under a memorandum of understanding between the TradeWind Consortium and the EWIS Consortium for the exchange of wind power related data to EWIS and grid related data to TradeWind. The interaction between the two consortia was supported by mutual participation in Project Advisory Boards.

STAKEHOLDER INTERACTION THROUGH SYNCHRONOUS ZONE SEMINARS

TradeWind organised topical Seminars in the major synchronous zones in Europe:

- GB and Ireland (Glasgow, 8 October 2007)
- UCTE (Berlin, 6 December, 2007)
- Nordel (Trondheim, 24 January 2008)

These seminars allowed the stakeholders in the various regions to learn about the objectives and work of TradeWind. In addition, valuable region-specific input on grid and market aspects was provided through the close interaction with these local stakeholders. Information and presentations from the seminars can be seen on the TradeWind project website: www.trade-wind.eu

1.5 Structure of the report

This report will outline the method, approach, analysis, conclusions and recommendations of the TradeWind consortium. Where relevant, references are made to further information from specific TradeWind reports and data sets from the various work packages. These reports can be found on the TradeWind project website.

The simulation and further analysis are based on geographically distributed projections for wind power capacity in Europe until the year 2030. Snapshots of the national projections have been made for various scenario years, and for each year into Low, Medium and a High estimate. In Chapter 2, these wind power capacity scenarios are explained, as well as how to transform them into regional wind power time series to be used for the power flow simulations in the grid. Chapter 2 also deals with the forecast errors of aggregated wind power.

Chapter 3 describes the power flow simulation method used in TradeWind and its main elements: the representations of the network, the market models, the inputs, outputs and models used in the power flow simulations of the European transmission systems.

Using the scenarios in Chapter 2 and the method described in Chapter 3, simulations have been made of the effect of wind power on transmission systems in Europe. Chapter 4 looks at the cross-border power flows and how they are impacted by weather systems moving over Europe, causing large-scale variations in the aggregated wind power resource. The chapter also demonstrates the importance and limitation of wind power forecasting in the cross-border planning of system operation.


Source: LM Glasfiber

Power flow simulations are also the basis for the analysis in Chapter 5, which looks at the benefits and costs associated with different options for transmission upgrades, in parallel to the expanding wind power capacities. The grid scenarios include gradual onshore reinforcements, mainly of interconnectors, as well as possible configurations of offshore transmission networks based on offshore wind power projects in the North Sea and the Baltic Sea.

Chapter 6 analyses the contribution of wind capacity to generation adequacy on an international level. Using TradeWind's basic scenarios and data, the chapter explains how aggregating wind power from several countries increases the capacity credit at a European level, and the effect this could have by 2020.

Chapter 7 looks at the effect the design of the power market has on its efficiency when there is a large amount of wind power. Market designs can differ in terms of time flexibility, market aggregation and interconnector capacity allocation. The chapter demonstrates the consequences of good market design with help of the selected market indicators, calculated via market simulation tools using the TradeWind wind power scenarios.

The findings and conclusions are summarised in Chapter 8.

The report contains references to specific topical reports produced within the project period.


Source: Fördergesellschaft Windenergie

2. Wind power scenarios

2.1 General

Several sets of input data were used for the studies reported in later chapters. These are described in more detail below.

2.2 Wind power capacity scenarios

Wind power capacity estimates were obtained for all EU-27 countries as well as Norway, Switzerland, Croatia and some of the Balkan States. A number of key partners were identified who provided data for each country.

Capacity estimates were requested for the following 'target years': 2005 (the latest confirmed figures at the time of the work), 2008, 2010, 2015, 2020 and 2030.

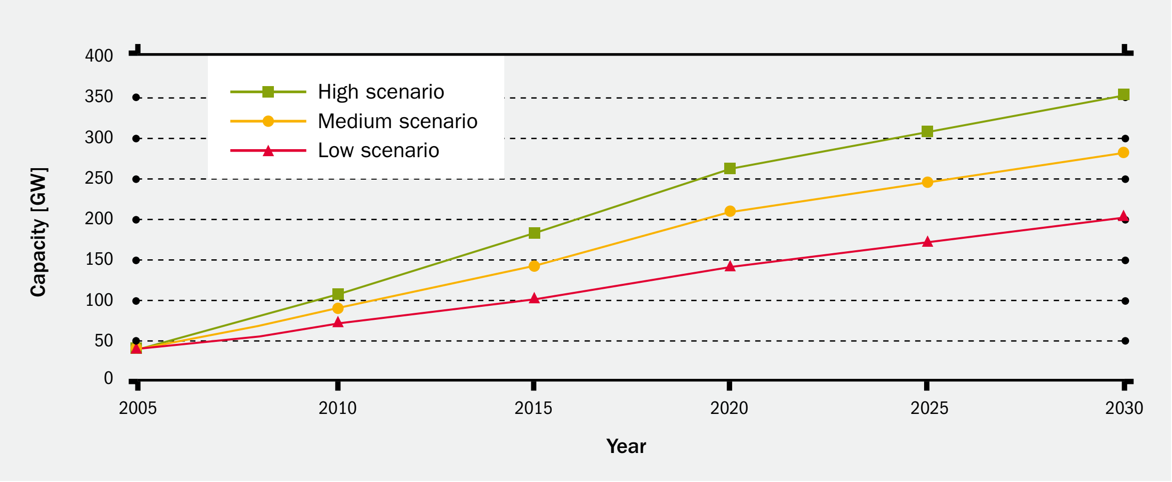
High, Medium and Low scenarios were defined for each year, where Medium is the most likely outcome and High and Low are the highest and lowest 'credible' outcomes. The capacity estimates for the High and Low scenarios are subjective: they are there to provide limits to allow credible sensitivity studies. It should be understood that the reality will almost certainly differ from these estimates. Historically in Europe, wind power capacity has increased much faster than even the highest estimates. However, the range of possible future outcomes is expected to lie within the High and Low scenarios, and most are likely to lie close to the Medium scenario.

The total figures for each of the scenarios are shown in Table 2 and Figure 1.

Year	2005	2008	2010	2015	2020	2030
Low scenario	42.2	57.2	72.3	103.3	143.9	203.3
Medium scenario	42.2	66.5	90.0	143.7	205.8	279.6
High scenario	42.2	78.1	108.2	185.0	263.4	351.1

TABLE [2]: **Total wind generation capacity by scenario and year (GW).**

FIGURE [1]: **Total wind generation capacity by scenario and year.**[f]



The figures for the Medium scenario were similar to EWEA's forecasts at the time, of 80 GW for 2010, 180 GW for 2020 and 300 GW for 2030. This indicated that the data gathered and used for TradeWind is in line with EWEA's forecasts.

The wind capacity data was then regionally clustered - the wind capacity estimates were mapped to geographical regions related to the nodes for which wind speed data are available. The wind speed data is discussed further below.

Regions were defined in a complex process which took account of the following factors:
- Location of areas known to have good wind resources
- Elevation
- Wind speed data nodes (i.e. the allocation of exactly one wind speed node to each region)
- Terrain types (discussed further below)

The wind speed data node chosen for each region does not necessarily lie within the region: instead the node nearest to the expected location of wind generation was chosen.

A total of 138 regions were defined. Wind capacity estimates for each of the target years were then defined for each region. For countries with several regions, the national capacity estimates were subdivided between the regions, based on knowledge of areas where there is likely to be a higher development of wind energy.

Finally, the installed wind capacity in each region was split between terrain types, depending on the characteristics of the region.

2.3 Wind speed time series

The original intention in the project proposal was to use Reanalysis data sets to produce short time-series of wind speed data at a large number of nodes across Europe. The nodes are shown in Figure [2]. The short time-series would be chosen to include events of interest, such as the passage of storms, and periods where there were anticyclonic conditions (low winds) in some areas of Europe and high winds in others. In practice, it was found that the power system simulations reported in later chapters were sufficiently fast that it was possible to use a year of wind speed data at a time, rather than selecting specific events.

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[f] The total wind power capacities shown in the graph may slightly deviate from the numbers used in the simulations due to differences in the countries surveyed and the countries simulated. The effect on the results however is negligible.

FIGURE [2]: **Reanalysis data nodes covering Europe.**

The Reanalysis data was chosen because at the time, this was the only data which covered all of Europe in a consistent manner and thereby best suited the needs of TradeWind. More detailed data sets are of course available for individual countries or regions, but there would have been significant cost in obtaining this data and then in creating a single consistent data set.

The data was only available at six-hourly intervals. Interpolation to hourly intervals was carried out, and it was found that linear interpolation was the best method.

The effect of the six-hourly basic interval is that changes in the wind speed over a region which occur at faster timescales will not be represented in the data. Therefore very rapid changes in wind speed (such as the passage of a storm front) will not be represented accurately and in general intra-day changes will be underestimated.

The terrain in which a wind farm is located has a significant effect on the wind speeds and therefore terrain wind speed adjustment factors were defined, for three broad classes of terrain appropriate for commercial wind farms:
- Lowland (up to 400 m above sea level)
- Upland (over 400 m above sea level)
- Offshore

The corresponding terrain wind speed adjustment factors are applied to the hourly wind speed time series in order to obtain a more representative hourly site wind speed time series.

Adjustment factors for hub height and wind shear exponent were also defined for each of the terrain classes. For the Lowland class, it is anticipated that turbine hub heights will increase in future, and so different factors were used for future years.

After applying all factors, the Reanalysis data produces mean wind speeds representing typical regional hub height wind speeds with an uncertainty of approximately 1m/s in areas appropriate for wind farms across Europe, with the following exceptions:
- North-east Spain
- Southern France
- Greek islands

In these areas, localised flow channelling and thermal effects result in wind speeds that are not captured by the Reanalysis data.

The final data set covered the seven years from January 2000 to December 2006.

2.4 Aggregated (regional) wind power time series

Annual capacity factors calculated from the Reanalysis data (with all relevant adjustment factors applied) were compared with the data available on the annual capacity factors of operating wind farms.

Based on this, further wind speed correction factors were calculated for the upland and lowland terrain categories, which brought the capacity factors into general agreement with expectations for likely onshore wind sites in Austria, Belgium, Germany, Great Britain, Greece, Ireland, Italy, the Netherlands, Poland and Spain.

It was then necessary to define the method to convert the hourly wind speed data to hourly wind power production data for wind farms in any particular area. This was done using an equivalent wind power curve (EPC). Future developments in wind turbine design and the implications for the EPC were considered up to the year 2030.

The EPC includes factors such as spatial averaging across large geographical areas, array losses within

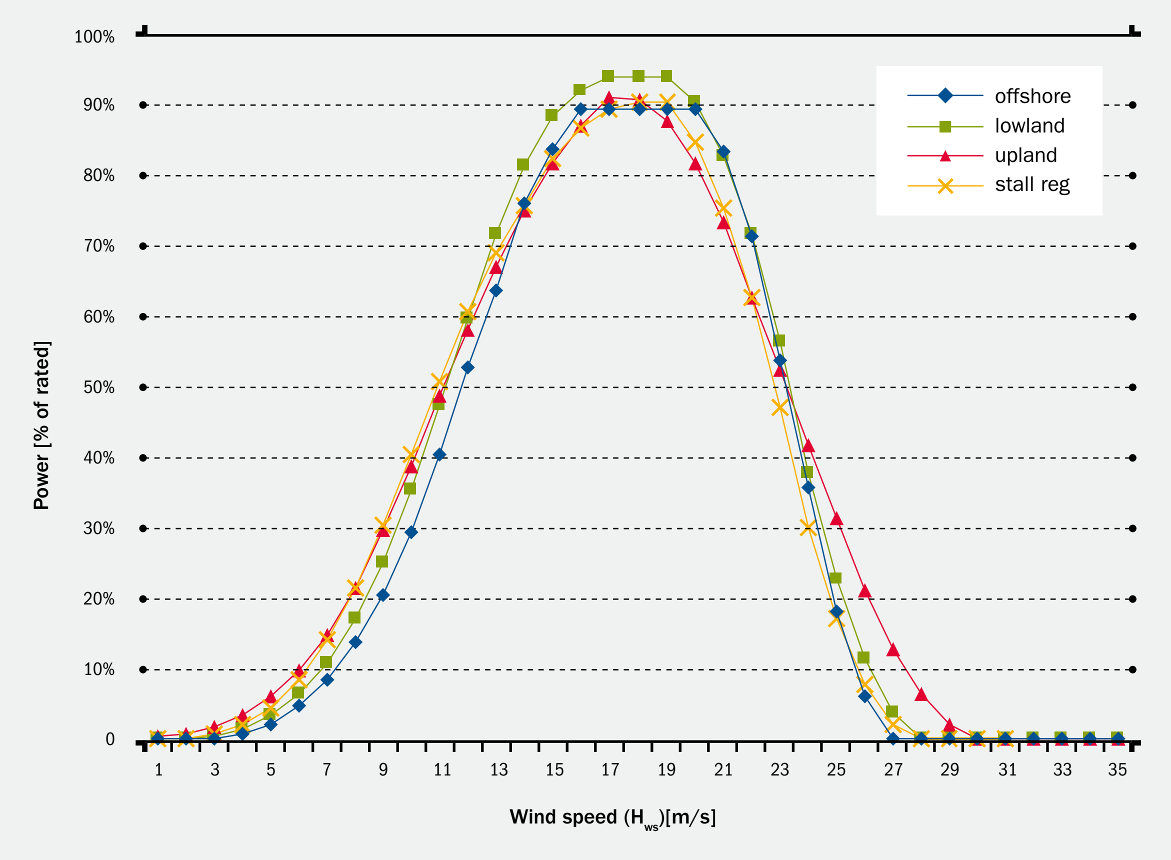

FIGURE [3]: **Equivalent regional power curve models for present day. Blue, green and red curves represent pitch regulated wind turbine concept.**


Source: APPA

each wind farm, topographic losses, electrical losses and availability, and it estimates the effect of possible future developments in wind turbine power curves and hub heights. After assessing EPCs with different wind turbine concepts (e.g. stall, pitch) it was found that the wind turbine technology only had a minor influence on the shape of the EPC. Accordingly, wind turbine control concept (stall/pitch) was not considered as an additional variable in further analysis.

2.5 Added variability to wind power

Comparing measured time series of wind power in western Denmark to the wind power time series described above has shown that the statistical distribution of the wind power time series used agrees quite well with the statistical distribution of the actual wind power. However, using the time series above leads to the intra-day variability of the wind power being underestimated. This is indicated by the time series shown in Figure 4, where the measured time series seen to exhibit sharper changes than the Reanalysis-based time series.

In principle, this missing variability will have an influence on the operation of the power system, because other power generation has to be ramped up and down to compensate for wind's variability. However, it depends on the applied power system simulation tool if this is actually reflected in the result. If the tool is simulating each hour independently, like PSST where the focus is on the grid, then it is sufficient to have the right statistical distribution of the power. If, on the other hand, the tool takes into account start-up costs and start-up time of power plants like the WILMAR market model (see Section 3.6), then more realistic simulations can be obtained with more realistic intra-day variability.

In order to provide more realistic wind power variability for the WILMAR market model simulations, stochastic variability was simulated and added to the wind speeds before the wind power was calculated. The added variability was calibrated so that the power spectral density (PSD) of the simulated wind power, i.e. the variability of the simulated wind power, is similar to the PSD of the measured power. This is illustrated in Figure 5,

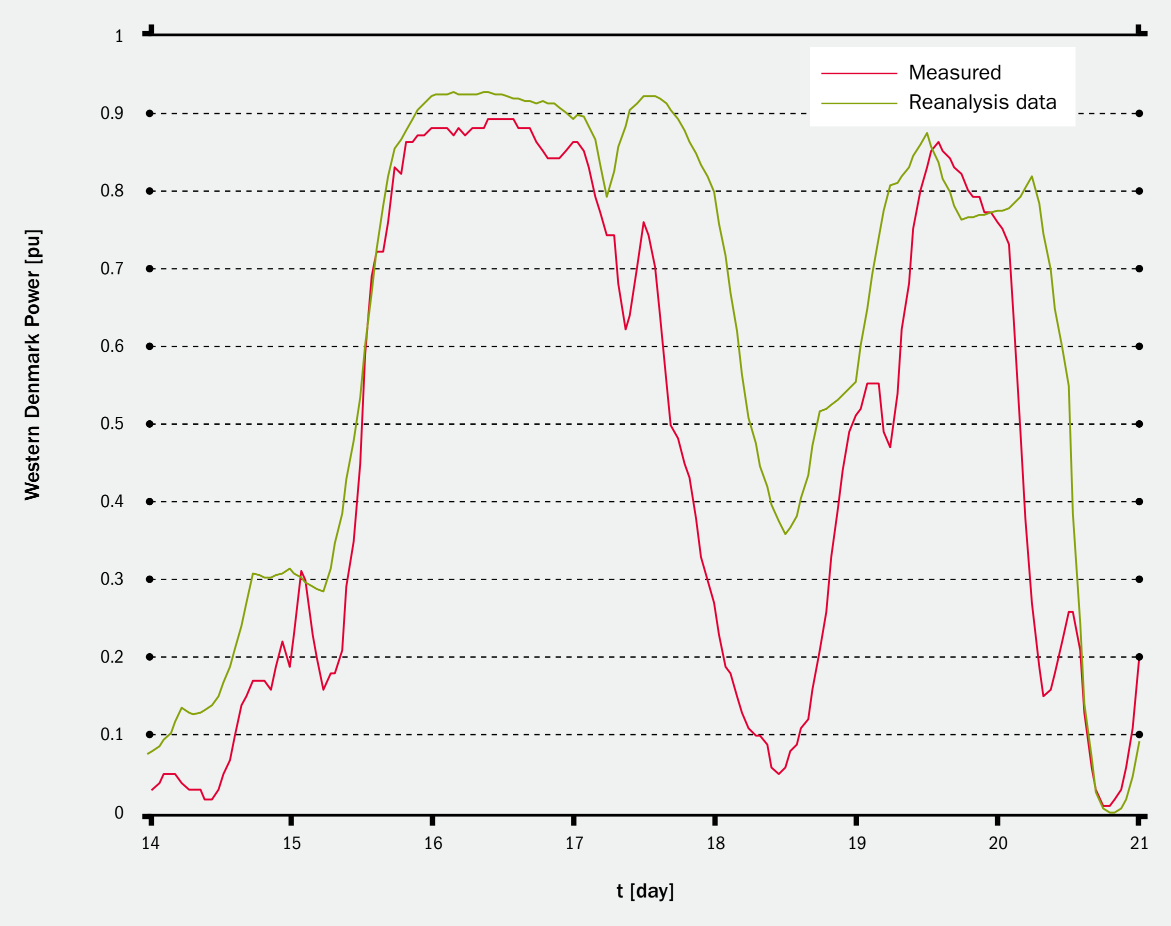

FIGURE [4]: **Measured historical wind power production in western Denmark for third week in 2000 compared to simulated data, using reanalysis wind data.**

where historical data for the year 2000 is analysed. The Reanalysis-based (green) PSD is generally lower than the measured (blue) PSD for frequencies higher than 10^{-5}, while the PSD of the simulated power with added variability (red) is much more similar to the PSD of the power measured.

2.6 Forecast error of aggregated wind power production

When analysing a power system, it is necessary to include an assessment of the potential error margin for wind production predictions. In this way, it is possible to simulate the power generation scheduling process as carried out by system planners and operators.

The wind production from a region is of interest, not from specific wind farms. Prediction accuracy has improved steadily over recent years. Any errors depend on the forecasting horizon (the amount of time ahead the prediction has to be made for), the predicted wind speed, and the quality of the Numerical Weather Prediction model and the short-term prediction model, amongst other factors.

Based on published work and project team members' own experience, estimates of forecast error achievable by modern forecasting techniques were produced for a range of forecast horizons.

Importantly, it was found that the amount of prediction errors for wind power in a geographical region diminish as the region size increases, especially for shorter forecast horizons.

FIGURE [5]: **PSD's of measured and simulated wind power production in western Denmark for 2000-2002.**

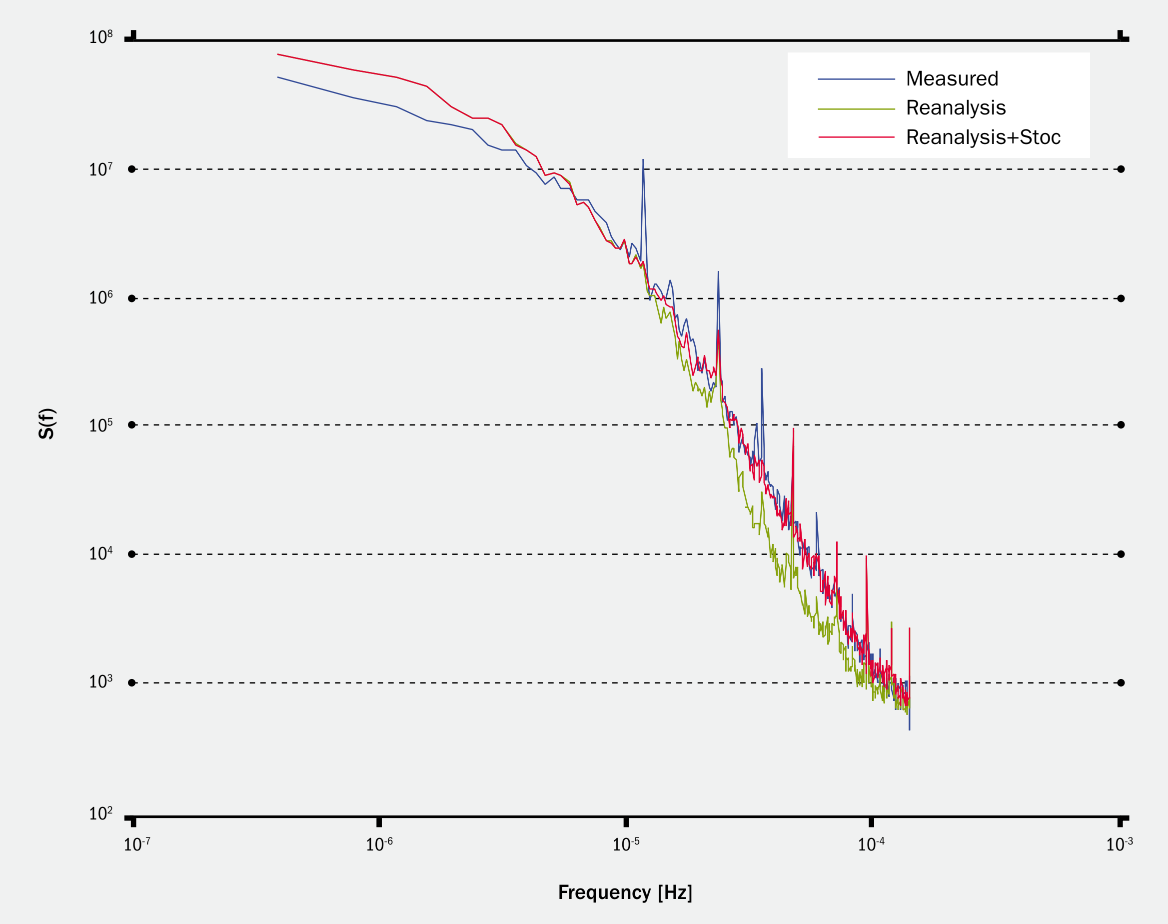

FIGURE [6]: **Mean absolute error as % capacity – year 2004 Finland.**

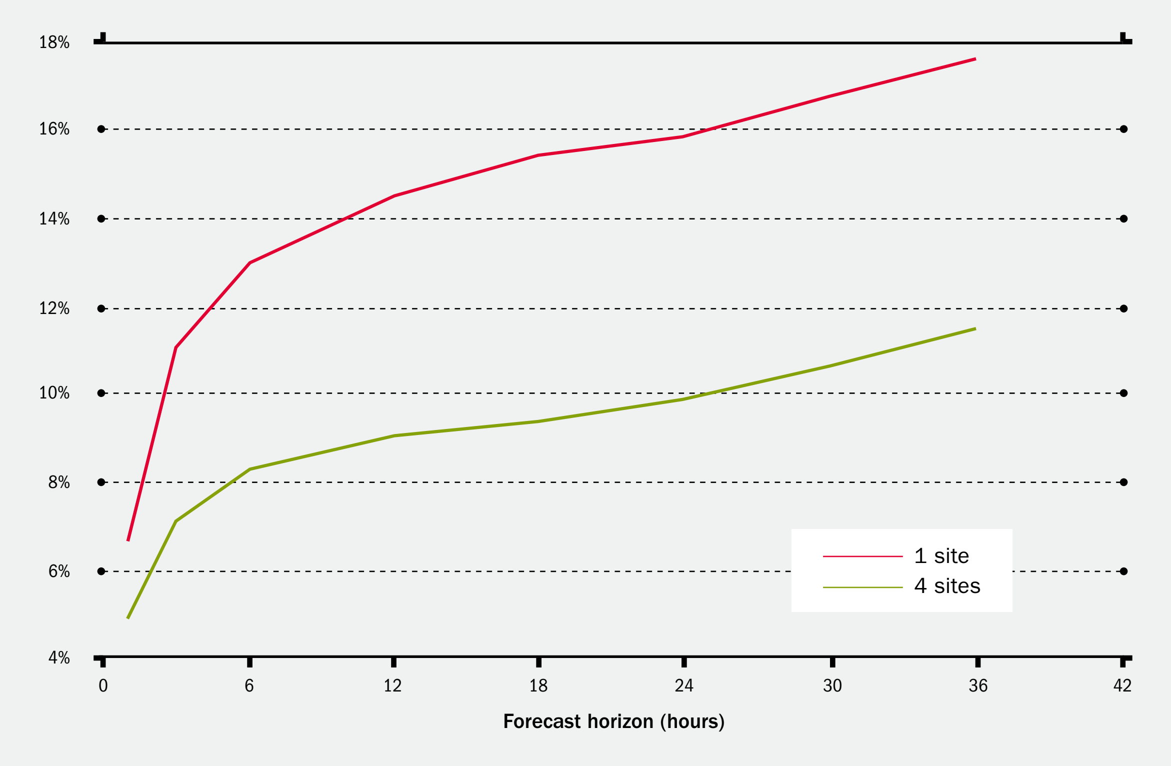

Figure 6 illustrates this by showing prediction errors (mean absolute) for a single site and for the aggregated output of four sites (with a maximum distance between them of 380 km), for a range of forecast horizons.

Work in the EU ANEMOS project [4] showed that prediction models perform very similarly on simple terrain, but have significant differences on complex terrain.

2.7 Summary

Wind power capacity scenarios were collected for the TradeWind target years, and for the Low, Medium and High Scenarios. These were converted into hub height and terrain specific wind power time series, with a time step of one hour, for a grid spanning the whole European area studied. Comparing these time series with observed wind power production in specific areas helped to establish necessary calibration factors in specific regions of Europe (North Sea offshore, Spain).

A scoping study was made on wind power forecast errors at European scale. Prediction errors for the aggregated wind power over a geographical region reduce as the region size increases, especially for shorter forecast horizons.

The intra-day variability of wind power will be underestimated with the linearly interpolated Reanalysis data, but is acceptable for the power flow simulations.

Source: GE

3. Simulation inputs, approach and models

3.1 General

TradeWind carried out simulations of the European transmission network and the power market as a basis for its analysis and recommendations. This chapter gives information on the simulations, including the assumptions made regarding power, transmission representations, input data and modelling tools both for power flow analysis and for market analysis. The chapter also briefly discusses the validation of the simulation approach.

3.2 Generation

3.2.1 WIND POWER

As described in Chapter 2, the installed wind power capacity for each country is divided into different "wind regions". The simulation program linked these wind regions to the grid model zones within each country. For this purpose, TradeWind created specific procedures for allocating the wind power generation to the transmission buses in the different synchronous zones [5]. In total, 128 wind regions were defined within the geographical area of the European grid model. These regions were then divided into 56 different grid zones. The total wind power production in a grid zone is the sum of the production of all the wind regions of that zone. Wind speed data from the Reanalysis global weather model, combined with regional wind power curves and wind speed adjustment factors (see Chapter 2) is used to generate synthetic wind power time series for the different grid model zones.

Aggregated wind farms are modelled as generators with maximum power equal to the available wind power for the specific hour. The minimum production is set to zero so that it is possible to reduce the wind power output in constrained areas. The marginal cost is set low, so that wind power plants always will produce if not limited by grid constraints.

WIND YEAR FOR SIMULATIONS

The simulations were made for one year selected out of the seven (2000-2006) of available Reanalysis data. TradeWind calculated annual capacity factors from the wind data for each country and identified the year 2004 as representing the most challenging cases for wind integration because of the high winds and high capacity factors experienced. These elements were most prevalent in Germany, the EU country with the highest amounts of installed wind power capacity.

3.2.2 OTHER THAN WIND GENERATION

There are two scenarios for the development of power generation capacity [6]:

- "Conservative" Scenario A: only new generation projects known to be certain to ahead are counted. This scenario is used to identify the expected need for new investments in power generation.
- "Best estimate" Scenario B also counts power plants that will probably be commissioned, based on information given by the TSOs in 2007.

The generation scenarios A and B differ from each other only in the UCTE zone, while values of the synchronous zones Nordel, GB and Ireland are the same in both scenarios. The values for Nordel, GB and Ireland were obtained from EURPROG Statistics [7]. The year 2030 is only specified for scenario B, and all the values come from EURPROG Statistics.

For each of the simulation years the generation capacity given was taken for the third Wednesdays in January and July. The type of generation is given as hydro, nuclear, fossil, renewable and 'not clearly identifiable energy source'. Fossil fuels included are lignite, hard coal, gas, oil or a mix of oil and gas. The installed capacity is the aggregated electricity generating capacity of the given type at the given area and year.

3.3 Demand (load)

For the Nordic countries the hourly load profiles were provided by Nordpool and the forecast by Nordel, by the National Grid for Great Britain and by Eirgrid for Ireland, while UCTE provided the load data for all the other countries.

Hourly load profiles for each area were collected for a given year, 2006, and were normalised so that the total demand for a year was equal to one. The original load profile in each area in the power flow description is scaled with the normalised value and the total demand for given hour and year are simulated.

The load forecast used to scale each country's demand for the years 2007, 2008, 2010, 2015, 2020 and 2030 are based on EURPROG 2006 [8]. It should be noted that this data does not anticipate a reduction in demand as envisaged in the recent EU Energy Package or in EWEA predictions [9]. The total annual consumption for the various scenario years is given in Table A-2.

3.4 Transmission

3.4.1 GENERAL

The simulation approach focuses on analysing cross border power flows. The grid model used for the simulations is a combination of separate equivalent power system models of UCTE, Nordel and the GB and Ireland. The European grid model is built by combining these three models. The 2005 base model consists of 1,380 nodes, 2,220 branches, nine HVDC connections and 560 generators of other type than wind. Wind power production is aggregated into 129 buses in total. A description of the grid model can be found in the WP3 report [10] and its appendix [11].

3.4.2 NETWORK REPRESENTATIONS FOR THE VARIOUS SYNCHRONOUS ZONES

3.4.2.1 UCTE

Due to delays in obtaining the high voltage grid data from the European TSOs, the TradeWind consortium had to base its investigations on public data. As a starting point, the group chose the approximated UCTE network created by the team of Professor Janusz Bialek of the University of Edinburgh [12].This network covers the former first UCTE synchronous zone (i.e. excluding the Balkan states, Greece, and so on). It is a patchwork of publicly available data such as national generation levels, peak load, power flow exchanges (UCTE), generation/substation data obtained from the websites of individual TSOs, geographic information on population and industry. The electrical parameters for transmission lines were estimated using typical impedances based on the measured lengths and voltage levels given on the publicly available UCTE network map. Transmission lines were assumed to have standard Ω/km values, based on their lengths and voltage levels, which included 220kV and above. The network covers some 1,200 nodes and some 380 generators. In order to simulate other time horizons, TradeWind added recent grid reinforcements, again based on public data. Additions to the former second UCTE synchronous zone have been made as envisaged by Professor Bialek using documents like UCTE SAF reports and SYSTINT Reports on European, CIS and Mediterranean Interconnection.(g) The network size, with these additions, is about 1,381 nodes (of which 568 are generators) and 2,211 branches. This meant the UCTE network was up-to-date until the end of 2006.

UPDATED UCTE NETWORK REPRESENTATION: UCTE 2008 RESEARCH MODEL

UCTE provided TradeWind with the UCTE 2008 Research Model. This data set describes the winter and summer system cases for 2008. Since the data set only became available at the end of TradeWind's simulation phase, only a very limited amount of

Source: EWEA/Winter

simulations could be performed with this network representation. This more detailed model represents the grid topology fully, as it depicts the current network structure with all voltage levels and substations. It includes all the UCTE member countries. In contrast to the approximate model, the parameters provided include current transmission line and transformer impedances. Moreover, the thermal line capacities on all circuits are also included. The size of the model is however, significantly more with 4,339 nodes (of which 943 are generators) and 7,292 branches (the capacities of 5,677 of which are given).

Although the network dimensions of the detailed model are significantly greater than the Edinburgh model, it can provide an improved platform on which to represent the dispersion of wind energy on the grid and thus better ascertain the impact on internal as well as cross border power flows. The thermal line capacities of circuits internal to the Member States is very significant to this point, as wind energy constrained by local or internal transmission limitations will now become visible. Further, transmission congestions internal to each country and how these may limit international energy trade may now be depicted.

3.4.2.2 NORDEL

The basis for all calculations performed on the Nordel power system is the 23 generator model of the Northern European system. The model has been developed at SINTEF Energy Research through several steps and updated with recent grid and generation data for the use in the TradeWind project. The development of this model is described in references [10] and [11]. The original Nordel system includes a bus representing west Denmark and a bus representing Germany. These buses were removed from the Nordel grid used here, since they are part of the UCTE grid model. The HVDC connections to west Denmark and Germany were kept since they link the Nordic grid model with the UCTE grid model. The grid model is shown in Figure 7.

The 23 generator model was suitable for the TradeWind study as it has a similar power flow to a full-scale model of the Nordel system. Its reduced size and significant accuracy make the 23 generator model the best option for active power flow analysis. The lines and generators are located and adjusted in such a way as to reflect the real production and the most interesting bottlenecks in the Nordel system to a significant degree. The impedances are adjusted so that the power flow will correspond to a significant degree to a full-scale model.

In Figure 7 the locations of the different generator equivalents in the 23 generator model are indicated. The node number of the different generators is also shown.

3.4.2.3 GB AND IRELAND

All network models have focused on interconnections between areas and cross-border capacities. Therefore, with a few exceptions, no capacity limitations were modelled for internal branches within each defined area for the UCTE and Nordel systems. Great Britain and Ireland were simply modelled as two separate areas (see Figure 8). Internal transmission constraints within GB and Ireland are thus not represented in this study, only the HVDC connection between the two systems and the HVDC link to France.

3.4.3 LINKING THE SYSTEMS TOGETHER

The synchronous zones are linked by HVDC connections. These are modelled as interdependent loads with opposite signs on each side of the connections. An important feature of the model is the ability to optimise the utilisation of the HVDC links by considering HVDC power flows as optimisation variables at zero cost, while the transfer capacities on the connections remain a restriction.

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[g] Available at www.ucte.org
and at www.eurelectric.org

FIGURE [7]: **The Nordic grid equivalent. The numbers corresponds to generator buses. Load buses are not shown.**

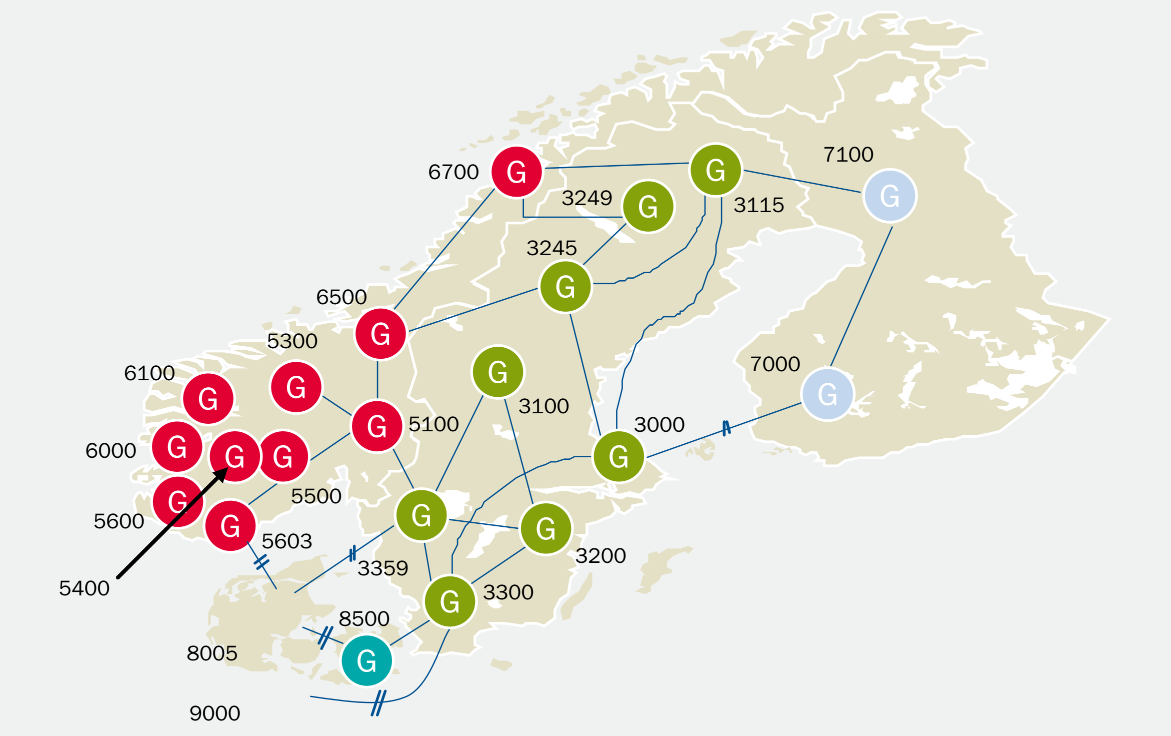
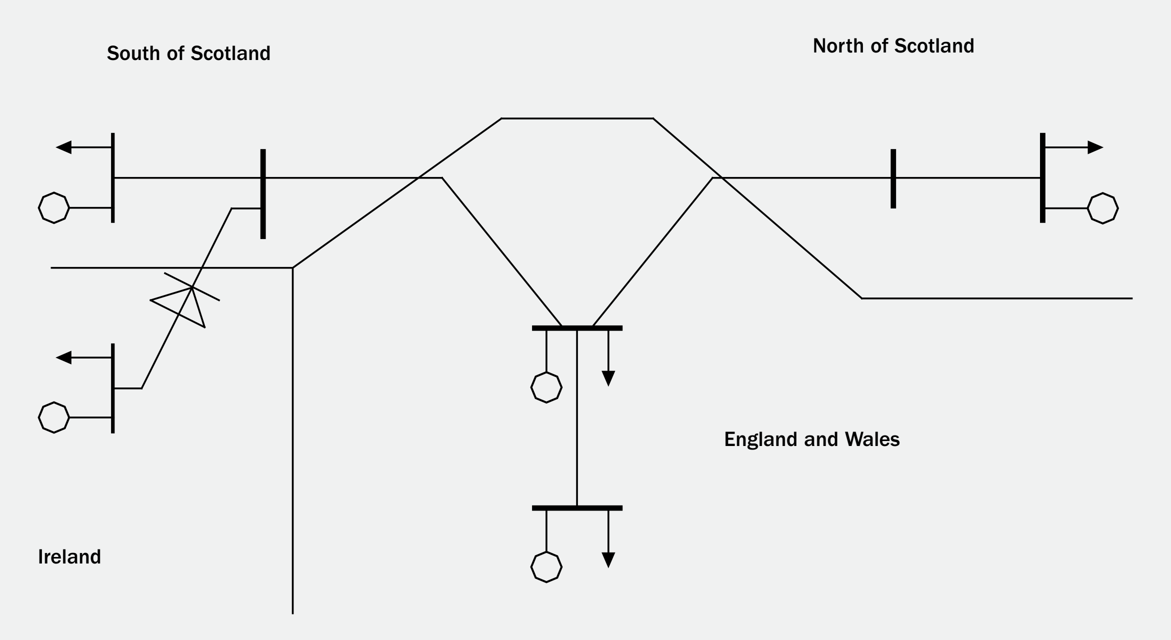


FIGURE [8]: **Great Britain and Ireland system (Ireland + Northen Ireland) grid equivalent.**



3.4.4 DEFAULT NETWORK SCENARIOS: FUTURE LINES

Future HVDC and HVAC lines are included in the model. Table 3 gives an overview of the planned new interconnectors. The simulations include the new lines from the year in which the lines are scheduled to come into operation.

YEAR	CONNECTION	CAPACITY [MW]	TYPE	INFO
2008				
	BE - FR	400	AC	Chooz - Jamiolle - Monceau
	GR - MK	1,420	AC	Bitola - Florina
	AT - CZ	1,386	AC	2d line Slavetice - Durnrhor
2010				
	ES - FR	3,100	AC	France – Spain: eastern
	DE - DKW	1,660	AC	Upgrading of Jutland - Germany
	NL - NO	700	HVDC	NORNED
	DKW - DKE	600	HVDC	Great Belt
	IE - GB	500	HVDC	East-West interconn.
2015				
	IT- SI	3,100	AC	Udine - Okroglo
	NO - SE	800*	AC	Nea - Jarpsstrommen
	PT - ES	1,500	AC	Valdigem – Douro Int. – Aldeadavilla
	PT - ES	3,100	AC	Algarve - Andaluzia
	PT - ES	3,100	AC	Galiza - Minho
	RO - RS	1,420	AC	Timisoara - Varsac
	NL - GB	1,000	HVDC	BritNed
	SE - FI	800	HVDC	Fenno Scan2
2020				
	AT - IT	3,100	AC	Thaur – Bressanone
	AT - HU	1,514	AC	Wien/Südost - Györ
	AT - IT	530	AC	Nauders - Curon/Glorenza
	AT - IT	3,100	AC	Lienz - Cordignano
	NO - DKW	600	HVDC	Skagerrak 4
	NO - DE	1,400	HVDC	NorGer

TABLE [3]: **New lines and their thermal capacity.**

3.4.5 TRANSMISSION RESTRICTIONS

The grid model includes restrictions on individual branches as well as on total cross-border transfer capacities. The restrictions on individual branches are usually the thermal line limit or the summed limits of equivalent of connections. In order to account for N-1 security limits (i.e. the ability to withstand line contingencies without overloads), cross-border limits for power exchange between countries and interconnected systems are usually lower than connections within the countries.


Source: EWEA/Roehle

These cross-border transfer limits, called Net Transfer Capacities (NTCs), are defined by the transmission system operators (TSOs). Due to the lack of detailed information, it was chosen to utilise the winter 2007-2008 working day peak hour NTCs throughout the whole year and for all years, thus taking possibly a rather conservative approach.[h] HVDCs are not included in the NTC restriction values used in the model, which means that the total transfer capacity between two countries is the NTC value plus the HVDC capacities.

A simplified approach is applied for estimating future NTC, whereby the grid model assumes that NTC increases linearly with the increase in the total line capacity between two countries:

$$NTC_{new} = NTC_{old} \frac{ATC_{new}}{ATC_{old}}$$

where:

- ATC – Available Transfer Capacity (sum of line capacities)
- NTC – Net Transfer Capacity.

3.5 Power flow simulation

3.5.1 PSST TOOL

The structure of the computer program used for simulating the European power systems is shown in Figure 9. The inputs to the program are the grid model, time series for load, time series for wind, generation capacity forecast for all generator types and generation costs for all generator types. Both the load and wind are given as relative hourly profiles for a given reference year. The actual load and wind power in any given hour can then be found using the total load in GWh and installed wind capacity in MW for all grid zones. The generation capacity forecast is given as the total installed capacity for a given year and country.

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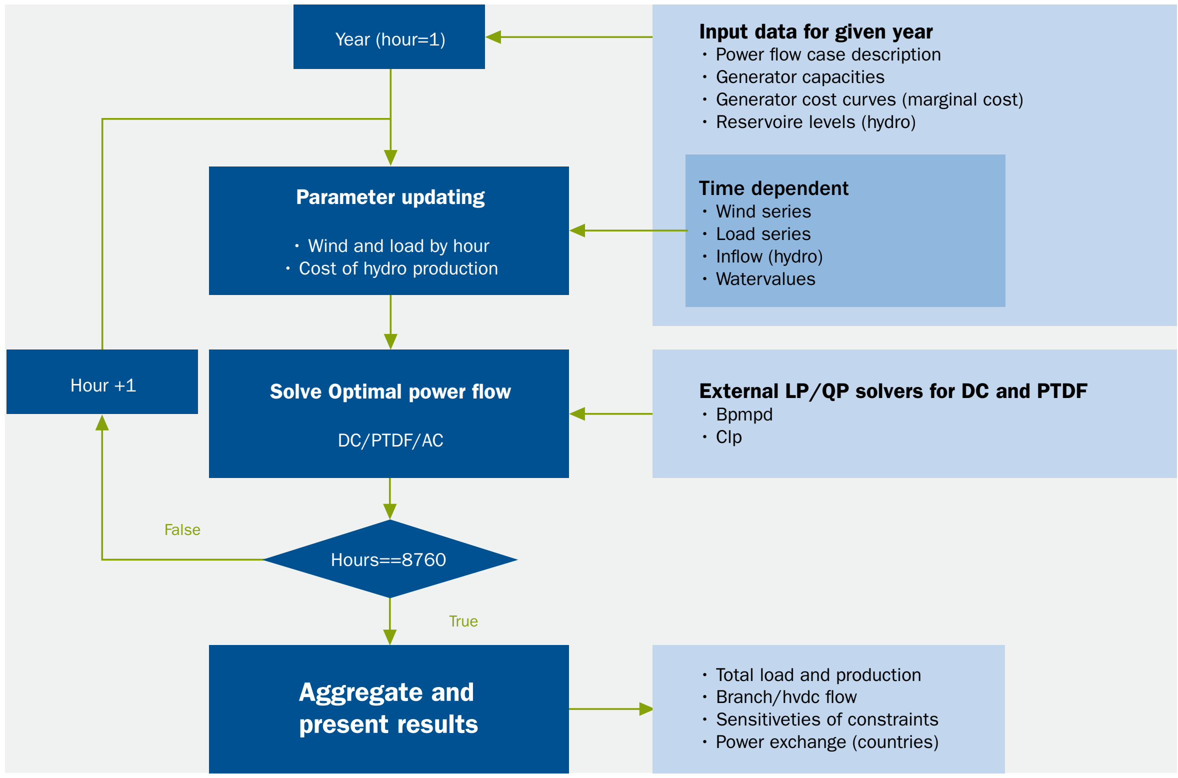
[h] The NTCs can only be defined by the TSOs as their values depend on issues of stability, for example. It is not possible to determine these values by simulation without detailed knowledge of the system and its operation.

FIGURE [9]: **Power flow simulation structure.**



Each hour the program updates the load, wind production and marginal cost of hydro units and runs an optimal power flow, which determines the power output of all generators and the power flow on all lines. In general, the power flow description can be either a DC, a PTDF or an AC formulation, though only the two first have been considered in this project due to the availability of data and also because of the time it would have taken to calculate the power flow for every hour in a year. In the end it was decided to adopt the DC power flow description [11].

The variables in the optimal power flow problem are the power output of all generators and the flow through HVDC interconnections. The power output of the generators depends on their maximum and minimum capacity, their marginal cost relative to other generators and the limitations on the amount of power that can flow through transmission lines.

The main results from a simulation are the hourly power production for each generator, flow and sensitivities for each branch and HVDC connection, and the total cost of production. Several simplifications and assumptions have been made in the study, notably:

- An ideal market is assumed, i.e. that the cheapest type of power generation available always replaces the most expensive type of generation (transmission limitations are taken into account)
- Start-up costs are not taken into account
- There are no requirements for reactive power support
- Wind uncertainty and allocation of power reserves are not incorporated
- The model does not include losses on branch flows and HVDC flows, nor does it include the costs of power transmission
- The strategy for use of hydro reservoirs is based on external water values
- Power plants are modelled as 100% available. The exceptions are nuclear plants, which have a reduced available maximum capacity depending on the time of the year due to revisions, and hydro plants, which may have limited available capacity depending on reservoir level and inflow
- The model does not consider fees for interconnector capacity allocation

Source: GE

3.5.2 LINE (PHYSICAL CAPACITY) AND NTC SENSITIVITIES

For the analysis of bottleneck situations in the transmission grid, congestions can be given a monetary value. TradeWind uses a parameter called 'sensitivity of transmission', which expresses the total amount of money that would have been saved on the market should a specific interconnection transmission capacity have been 1 MW larger (i.e. the marginal cost of transmission constraints). The sensitivity value unit is Euros (€)/MW. There are two sensitivity values calculated in the simulations: "sensitivity of power line capacity" and "sensitivity of NTC". Respectively, the two are calculated by assessing 1 MW increases in single interconnection line capacity or in NTC value. When the lines are not operating at their limit, or when cross-border transmission is below NTC, the respective sensitivity value is zero. Thus the sensitivity value indicates the level of congestion on the interconnection or cross-border concerned [10] [11].

As transmission restrictions are due to individual line transmission capacities and/or TSO-defined NTC values, the capacity sensitivities indicate the reason for the congestion:

- High and significant power line sensitivity value: possibly insufficient transmission (line) capacity on the cross-border link
- High and significant NTC sensitivity value: possible need for system reinforcements (not necessarily only on internal transmission bottlenecks, but also due to stability issues and so on) in at least one of the countries interconnected in order to be able to accommodate more cross-border transmission, and thus higher NTC values

3.5.3 VALIDATION

In order to assess the accuracy and quality of the model's performance, the results of the simulation results were compared to real data in order to check the following aspects:

- How well moving weather fronts and short-term meteorological phenomena were captured
- The accuracy of simulations comparing energy transfers on cross-borders on a yearly time scale and transmission bottlenecks
- Comparison with more detailed network model of UCTE

CAPTURING MOVING WEATHER FRONTS

Wind power variations in simulation results correspond to the actual production data, as do overall wind power production trends. However, the model falls short when it comes to accurately representing the ramping down rates. This was especially true for the rates calculated for the ramping down of wind power production, which were slower than the observed rates (Figure 10).

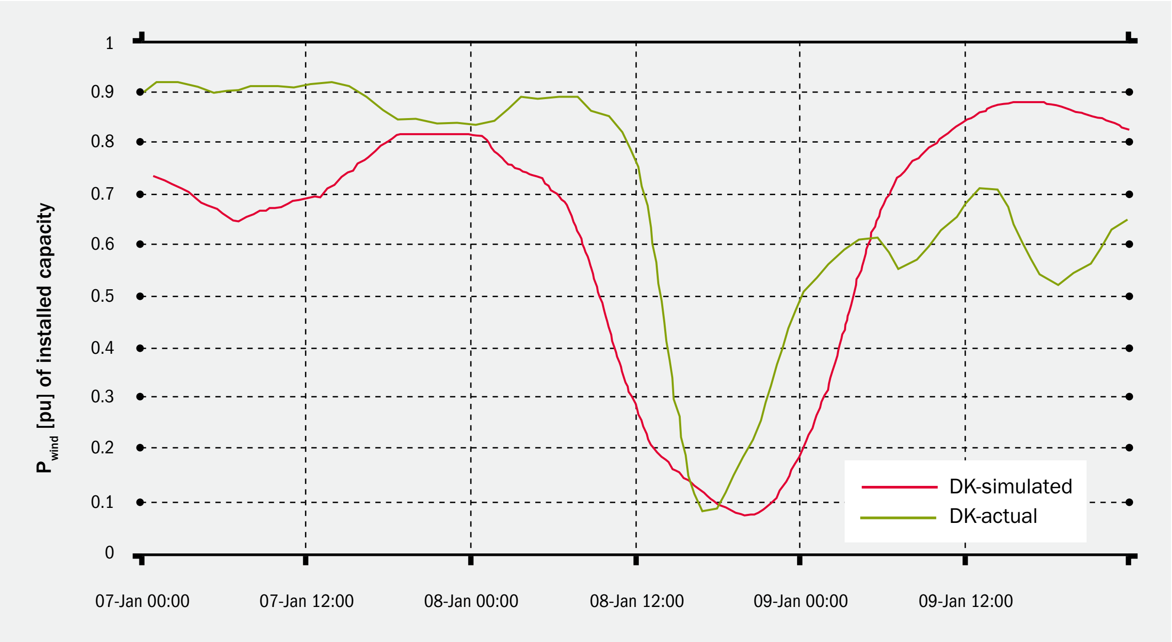
The difference between simulated and observed variation patterns is easily explained by the nature of the original Reanalysis wind speed data: six-hourly data interpolated to an hourly rate and calculated as the average over a fairly large area so that the highest and the lowest wind speeds are smoothed out. This makes the results less suitable for assessing system operation over short periods of time and in smaller balancing areas. However, for analyses that run over a year it should not be an issue if wind power production is not "correct" at one particular time as the wind speed is a random variable anyway.

COMPARISON OF SIMULATED AND ACTUAL TRANSMISSION DATA FOR 2005

TradeWind compared simulation results for 2005 with real data in order to assess the accuracy and quality of the model. The simulation was run with input data from 2005, but used working day NTC values from winter 2007-2008. The model assumes one single perfect European-wide electricity market, and thus the simulation results cannot really be expected to correspond accurately to the actual data. However, for quite a lot of the congested cross-borders identified as significant because of their high sensitivity values in the simulation (high marginal costs of associated transmission constraints) [13], development plans are being considered or construction has already started, based on sources like the UCTE Transmission Development Plan 2008 [23]. Also, the simulated yearly electricity transfers between countries are in line with the transfers actually made in 2005 (see Figure A-1 in annex).

Beside the simplifications and idealisations mentioned in the model, other reasons for the differences between the simulation and reality include the use of a single NTC value set for the whole year, and other imperfections in the modelling due to the lack of availability of more precise information on the power system (such as generation or the network).

FIGURE [10]: **Wind power production in Denmark during Gudrun/Erwin passing in the afternoon of 8 January 2005. Simulation vs. actual.**



COMPARISON WITH UCTE'S MORE DETAILED NETWORK MODEL

A comparative analysis was carried out to confirm agreement between the TradeWind model (using the more approximate UCTE network) and the more recent, detailed UCTE network [14]. This analysis focused primarily in 2005, and examined:

- Congestion sensitivity sums over a whole year
- Power transfer duration curves
- The annual energy exchange on interconnectors

The annual energy exchanges for 2020 were also compared.

Comparing the congestion sensitivity sums revealed consistency between both models in terms of the interconnectors identified. It also showed which sensitivity sum method – the power line or NTC – produced greater correspondence to the significant interconnectors in each market as identified in WP7.1 [15].

In terms of the power transfer duration curves, it was found that most interconnectors gave similar results. However, in some cases differences were observed. These differences were either 1) a greater level of congestion on the interconnector or 2) a general shift in the predominant direction of the exchange.

Analysing the annual cross-border energy transfers for 2005 revealed that although the results for the detailed and approximate models were similar to each other, they also both corresponded to the actual energy transfers. This therefore confirmed agreement between the two models in terms of annual energy transfers for a single and perfect market but also showed that the results were similar to those from a real system.

The analysis of energy transfers was extended to 2020. The results were fairly similar, however some differences were observed. These may in part be attributed to the increased wind production in 2020 and the influence that internal constraints would have on power flows in the detailed model and the relative absence of these constraints in the approximate model. In the detailed model the wind energy produced is limited (by the internal constraints) and thus the power production pattern of both wind and conventional generation in both models would differ, resulting in differing power transfer duration curves and annual energy exchanges.

3.5.4 UNCERTAINTIES

TradeWind checked the sensitivity of the simulation results to study the possible bias regarding certain effects related to the basic assumptions (such as scenarios, wind data and so on). The year 2010 Medium wind power scenario is used as the comparison case in all sensitivity analysis simulations, because for later simulation years the model may not yet properly include the necessary reinforcements. In the evaluation of the results of later simulation years TradeWind has observed the results taking into account the possible effect of the higher wind power penetration.

SENSITIVITY TO WIND YEAR

Wind speed data from 2000-2006 was available for TradeWind's simulations. As stated in Section 3.2.1, 2004 was the year chosen for the simulations. TradeWind checked the influence of the wind year by comparing the sensitivities of power line capacity and NTC, as well as the energy produced by wind power in each country during the simulated year. The simulations showed that the different wind speed data years do not seem to have much influence on cross border congestion (evaluated over the whole year).

SENSITIVITY TO CONVENTIONAL GENERATION CAPACITY AND SENSITIVITY TO LOAD FORECAST SCENARIO

Sensitivity analysis – again for 2010 – showed that for most interconnectors the wind power scenario used (Low, Medium or High), the conventional generation development and the load forecast scenario do not make a significant difference to transmission congestion. Of these, the wind power scenario seemed to have the least influence. It should be kept in mind that the difference between the generation scenarios A and B in the study year is rather small, as are the differences between the wind power capacities. In later simulation years, these differences become significantly larger.

3.5.5 OBSERVATIONS REGARDING THE MODELLING

It is important to correctly model transmission restrictions (using accurate values for NTC and line capacities) because cross-border connections are often fully in use in one direction or the other. As a consequence, incorrect assumptions on capacity values widely impact power flow in meshed networks. Not all the necessary information was available in enough detail for the study, but the TradeWind consortium is reasonably satisfied with the data and model, and considers the results they yield valid provided the limitations are correctly mentioned alongside the results. Simulation of cross-border exchanges in the European power system gave results similar to the 2005 ones, with the real transmission and bottleneck situations experienced then. When the simulation differs from the observed values, it can be explained by modelling issues. TradeWind modelling assumes a perfect market and a single set of NTC values all the time for all simulation cases. Deviations are also caused by general modelling imperfections due to a lack of more precise information of the system, for example missing details on network and generation.


Source: http://energypicturesonline.com

3.6 Market models

3.6.1 GENERAL

This paragraph gives a brief description of the two models used in TradeWind for studying the efficiency of the power market, namely WILMAR and PROSYM.

Both models are sophisticated simulation tools for modelling realistic dispatch decisions in a market environment characterised by variable and stochastic resources. However, the models have different approaches to uncertainty. While in PROSYM, uncertainty is represented by the demand for spinning reserves, in WILMAR it is introduced via a stochastic scenario tree. Therefore, results from both tools cover different cases and parameters. Similar cases from both tools can not be compared directly, but they partly complement each other. The results of the market analysis are discussed in Chapter 7.

3.6.2 WILMAR

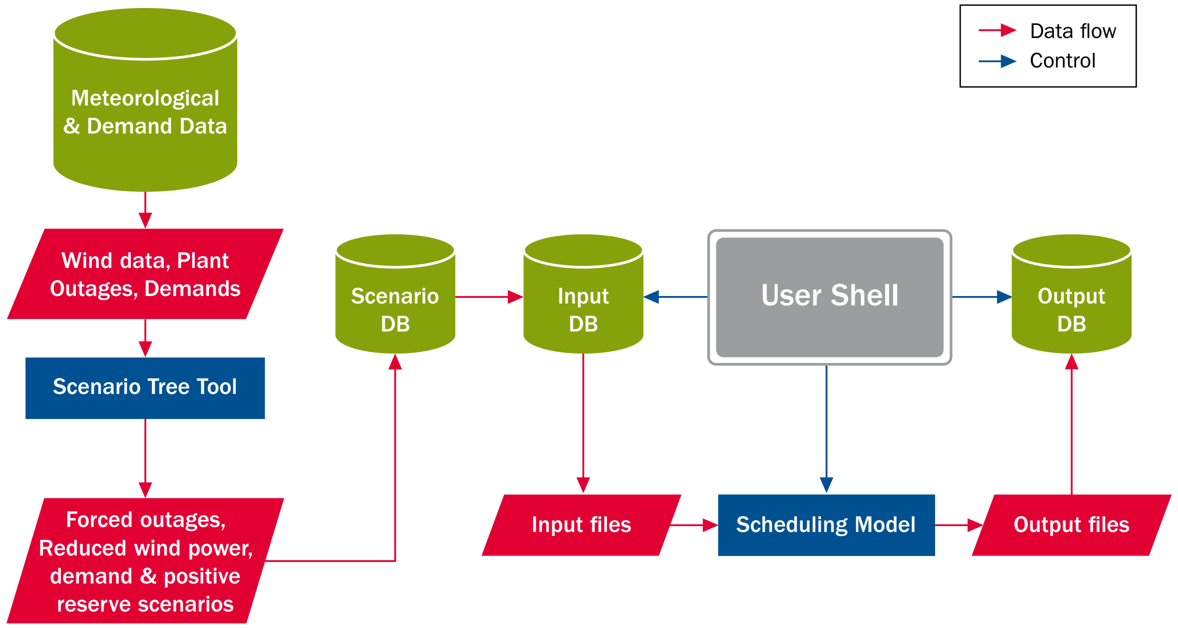
WILMAR PLANNING TOOL

The WILMAR planning tool is used to analyse the consequences of different market rules for a future European power system. The WILMAR planning tool consists of a number of sub-models and databases as shown in Figure 11. The main uses of the WILMAR planning tool are shown in the Scenario Tree Tool (STT) and the Scheduling Model (SM).

THE SCENARIO TREE TOOL

The Scenario Tree Tool generates stochastic scenario trees containing three input parameters to the Scheduling Model. These three input parameters are: the demand for positive reserves with activation times of longer than five minutes and forecast horizons for five minutes to 36 hours ahead (called the “replacement reserve”), wind power production forecasts and load forecasts. The main input data for the Scenario Tree Tool is the wind speed and/or wind power production data, historical electricity demand data, assumptions about wind production forecast accuracies and load forecast accuracies for different forecast horizons, and data on outages and the average (mean) time it takes to fix power plants. The demand for replacement reserves corresponds to the total forecast error of the power system considered, which is defined according to the hourly distribution of wind power and load forecast errors and to the forced outages of conventional power plants. Following this logic, it is assumed that the nth percentile of the total forecast error has to be covered by replacement reserves. The calculation of the replacement reserve demand by the Scenario Tree Tool enables the WILMAR planning tool to quantify the effect that partly predictable wind power production has on the replacement reserve requirements for different planning horizons (forecast horizons).

FIGURE [11]: **Overview of WILMAR Planning tool. The green cylinders are databases, the red parallelograms indicate exchange of information between sub models or databases, the blue squares are models. The user shell controlling the execution of the WILMAR Planning tool is shown in grey.**



THE SCHEDULING MODEL

The Scheduling Model is a mixed integer, stochastic, optimisation model. The stochastic input parameters are the demand for replacement reserves, wind power production forecasts, load forecasts and hourly time-resolution. The model minimises the expected system operation costs, which consist of fuel costs, start-up costs, the costs of CO_2 emission permits, and variable operation and maintenance costs. The expected system operation costs are taken over all given scenarios for the stochastic input parameters. Thereby the model has to optimise the operation of the whole power system without knowing which one of the scenarios will be closest to the stochastic input parameter, for example the actual wind power generation. Hence why some of the decisions, notably start-ups of power plants, have to be made before the wind power production and load (and the associated demand for replacement reserve) are known with certainty. The methodology ensures that these unit commitments and dispatch decisions can withstand the potential wind power prediction errors and load prediction errors as represented by the scenario tree for wind power production and load forecasts. Information about the WILMAR planning tool can be found in [16, 17, 18].

3.6.3 PROSYM® SIMULATION MODEL

The wholesale market simulation model PROSYM [19] is a probabilistic, hourly chronological power market simulation model (a stochastic linear optimisation model). The required pieces of input data are the annual hourly loads, the physical and operating characteristics of the generation plants and data for transmission areas and their links.


Source: EWEA/Boulley

The PROSYM probabilistic mode offers additional sub-method refinements such as distributed maintenance, detailed unit commitment and dispatch control, emissions as a proportion of the fuel burned, heat rate curves for the calculation of marginal costs (third-order equation).

The hour-by-hour model allows chronological events to be simulated such as plant availability, load changes, reserve changes at national level (due to changes in wind forecast), available transmission capacities and others. These events, together with transmission and plant constraints such as start-up times, thermal plant ramp rates, thermal plant up and down times, hourly spinning and non-spinning reserve, determine zonal market clearing prices[i] and volumes for each hour in each country using implicit allocation mechanisms.

Within PROSYM, the power system configuration shows the available power units and transmission capacity. PROSYM offers different modes of operation to take account of random effects such as outages. TradeWind used the preferred calculating method for its simulations, the convergent Monte Carlo method. This method causes carefully distributed outages throughout each period. A unit with an outage rate of x% is then available exactly 1-x of the time. This allows fast simulations of long periods of time, as far fewer iterations are necessary. This method can then help explain the effect of outages at different times of day and seasons of the year.

In addition, specific modules allow simulating a multi-area model with given transmission constraints to be simulated. Most of these characteristics can change every hour of the year.

PROSYM is made up of a suite of different modules that can be combined with the core PROSYM tool. TradeWind also considered the MULTISYM module. MULTISYM is a superset of PROSYM that is able to convert PROSYM into a multi-area model by taking transmission constraints into account. MULTISYM can handle mode independent and connected transmission areas with different topologies. When using the MULTISYM model, we limited the power exchange between countries according to the NTC values.

3.7 Summary of models and assumptions

TradeWind developed specific methodologies and sets of assumptions in order to simulate the effects of increasing wind power capacity on cross border power flows on the European network. Network data from the largest part of Europe (the UCTE area) could not be obtained directly from TSOs in time. Consequently, the investigations are based on information from the public domain and the best knowledge of the consortium members. The limitations associated with the use of the data and models are indicated together with the results. Comparing results on congestions and energy transfers at cross borders allowed us to check the accuracy of the TradeWind results. Further development and use of the UCTE research model made available by the TSOs are recommended to complement TradeWind's results.

In addition to the custom-made market tool used for the power flow simulations, two existing market models were used to analyse the efficiency of power markets with different combinations of market rules and wind power penetration levels.

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[i] Based on marginal cost approach


Source: EWEA/Winter

4. Effects of increasing wind power penetration on cross-border power flows in Europe

4.1 General

TradeWind simulated the impact of wind power on electricity exchange and cross-border congestions by using a flow-based market model (see Chapter 3). The model represents the European power system as a single market, and cross-border flow is restricted by individual circuit line capacities and NTC values. This chapter presents the results of the effect of wind power on the cross-border flows.

4.2 Impact of wind power on cross-border transmission

TradeWind studied the future impact of wind power on the interconnected European transmission grid by looking at the interconnectors and at bottlenecks and congestions. Simulations were run for 2008, 2010, 2015, 2020 and 2030 for three wind power capacity scenarios, Low, Medium and High. In order to put the future in the current perspective, the simulation years were complemented with the real moderate wind power capacity in 2005. The exact wind power capacity amounts for each year in all of the countries are given in Chapter 2. In order to evaluate the significance of different bottlenecks - to see how much they affect optimal energy exchanges and rank them according to the effect they had - the power line and NTC sensitivity values were studied.

4.2.1 IMPACT OF WIND POWER ON TRANSMISSION OVER THE INTERCONNECTORS

The simulations enabled annual power exchanges to be calculated for the different simulation years. The detailed results are presented in Figure A-2 in the annexe of this report. The most noticeable developments based on observations from the simulation results are:

- The 2008 and 2010 simulations show a significant export from Denmark to Germany. With the increased wind power capacity in northern Germany in 2020 and 2030, the situation changes to a more balanced exchange between Denmark and Germany. This in turn leads to higher exports from Denmark to Norway. The NorGer cable introduced in the 2020 and 2030 simulations is almost entirely used for transporting wind power from north Germany to south Norway. At the same time, south Norway exports power to the Netherlands via the NorNed cable. Norway thus becomes a transit point for export of excess power from Germany to Netherlands which has significantly higher marginal costs of power generation. This is as expected from the model, since HVDC links are modelled as fully controllable[i] and HVDC losses are not included.

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[i] Controllable HVDC link: due to its technical characteristics, the power flow over a DC link can be fully actively controlled, and with respect to power flow modelling in a system, such a link behaves almost identically as a generator.

- In the Nordic area, increased wind power generally gives higher transfers from Norway to Sweden, and from Sweden to Finland, Poland, Germany and Denmark (southern Sweden is partly used as transit point for exporting wind power from west to east Denmark).

- The increase in exports from Austria to southern Germany can be explained by the large amount of wind power in Austria in the 2030 Medium scenario (4,300 MW) as compared to the 368 MW in the neighbouring south-east of Germany.

- The high amounts of offshore wind power in Great Britain in the 2030 scenario give a significant increase in export to France, and also to the Netherlands via the BritNed cable that is included for 2015 and onwards.

4.2.2 SOME IMPORTANT OBSERVATIONS FROM THE CONGESTIONS IN THE SIMULATIONS

Since the HVDC connections are modelled as controllable, they are fully utilised most of the time in just one direction, independent of the wind power capacity scenario. Therefore, many of the interconnections containing HVDC connections are highly “congested”, that is to say, loaded to their maximum capacity. Some of the findings for specific connections are presented here:

- In the 2015 and 2020 scenarios, the cable between France and Great Britain and the planned cable between Netherlands and Great Britain is used most of the time in the direction towards Great Britain. However, in 2030, the number of congestion hours in the opposite direction increased, as Great Britain will have more installed wind power capacity and so will have more electricity to export.

- The interconnector between Austria and Germany does not have too much congestion linked to thermal line rating in 2015, but it does have significant amounts of congestion caused by NTC. As the export hours from Austria increase in 2030, there is a significant increase in number of power line congested hours in the direction of Austria, and wind power even adds to this increase.

- Increased number of congestion hours on the interconnector between France and Spain in the later scenario years (2030) is due to significant wind power capacity additions in France.

- As more wind power is installed in north-eastern Germany, the exchange between Germany and Poland changes from the Poland to Germany direction (2008, 2010) to a more balanced situation (2020 and 2030). By 2030, the NTC congestions are almost eliminated. Wind power causes this change on its own; the thermal generation scenarios for Poland show that cheap coal is gradually replaced by more expensive gas. At the same time, electricity consumption increases significantly.

- The Czech Republic experiences less of an increase in electricity consumption than Poland, but it sees an increase in nuclear power capacity. These developments would appear to be behind the main German import and congestions in the eastern part gradually switching from the direction of Poland to that of the Czech Republic. The congestion plots also show that the exports from Poland to the Czech Republic and the amount of congestion go down over time.

- The use of the Germany-Norway, Netherlands-Norway, Denmark-Norway and Denmark-Germany interconnections does not change much in the different wind power scenarios.

- Italy was an energy deficit area in 2005, and this situation is gradually worsening, and will cause power flow on the Italy–Greece link to be mostly in the direction of Italy regardless of the wind power scenario.

4.2.3 OVERALL OBSERVATION

The different simulations showed that many bottleneck situations do not change for different wind power capacity scenarios (Low, Medium or High), but do change significantly for the different simulation years (2008 up to 2030). For the simulation years 2008, 2010 and 2015, wind power generally has a low impact on congestion situations. For the later simulation years (2020 and 2030) increased wind integration causes more significant congestion, especially for connections between the following countries:

- France and its neighbours: Spain, Switzerland, Belgium, Great Britain
- Great Britain - Ireland
- Germany and its neighbours Austria and Sweden
- Sweden and its neighbours Finland and Poland
- Greece and Bulgaria

The impact of increasing wind power is not always in the same sense. For some interconnectors, increased wind power leads to less congestion on some cross-borders or interconnectors according to the simulations, and in other cases there are more instances of congestion on cross-borders or interconnectors in the high wind power capacity scenario simulation.

It is not only important to analyse how many lines are congested and how long for, but also how severe the congestion is. In 2005, the most congested connections were the ones between France and its neighbours Switzerland, Spain and Italy. The severity of the congestions of these lines does not change much in later years. Figure 12 shows the severity of the congestions for the ten most congested lines, using sensitivity to indicate the amount of congestion.

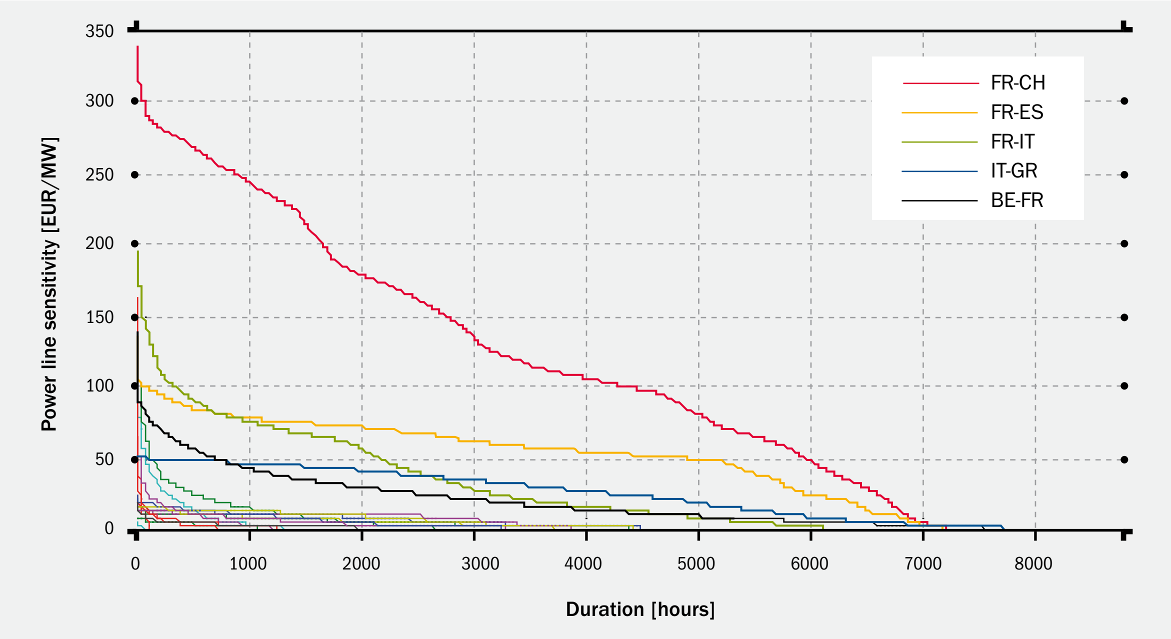
4.3 Impact of wind power forecast errors on cross-border flows

TradeWind investigated the uncertainty induced by the day-ahead wind power forecast errors on the predicted cross border power flows, using the increasing amounts of wind power corresponding to the scenarios chosen. Therefore, wind power forecast errors were calculated for all the various parts of Europe using a simplified approach. The standard deviation of the day-ahead forecast error is assumed to have a uniform value of 1.5 m/s and the forecast error at time t is assumed to be independent from the forecast error at t-1. In other words, forecast errors are not auto-correlated: a time series of wind speed forecast errors is generated randomly on the basis of a Gaussian distribution.

The projected wind power capacities for 2015 are used to analyse the effect of the wind power forecast error on the change in cross-border flow. The difference between actual and predicted power flow has been calculated for all cross-border connections, as well as the number of hours for which there is a difference. For most power lines the difference occurs during a significant part of the time, but the difference is mostly in the lowest 0-20% range of the line capacity.

This prediction error - the number of hours during which there is a difference between predicted (planned) and

FIGURE [12]: **Duration curves of power line sensitivity values on cross-borders in 2005 simulation. The most significant sensitivity value duration curves highlighted and named.**



actual cross border flow – does not change significantly with the chosen wind power scenario (Low, Medium, High). This effect is shown in Figure A-3 of the Appendix. Moreover, there is no significant change in the number of hours of deviation when the forecast horizon is changed from day-ahead to intraday.

From this analysis it can be concluded that since there is a significant probability of a difference between planned and actual cross border flow, integration studies should take the wind power forecast error into account.

4.4 Effect of moving weather systems on cross-border flows

This section investigates the movement of meteorological events and their effect on power balance and cross-border flows, both regional and national. The most challenging weather in terms of power flow variations for large power systems are deep, moving low pressure systems that cause high wind power production and storms that can cause wind farms to shut down suddenly.

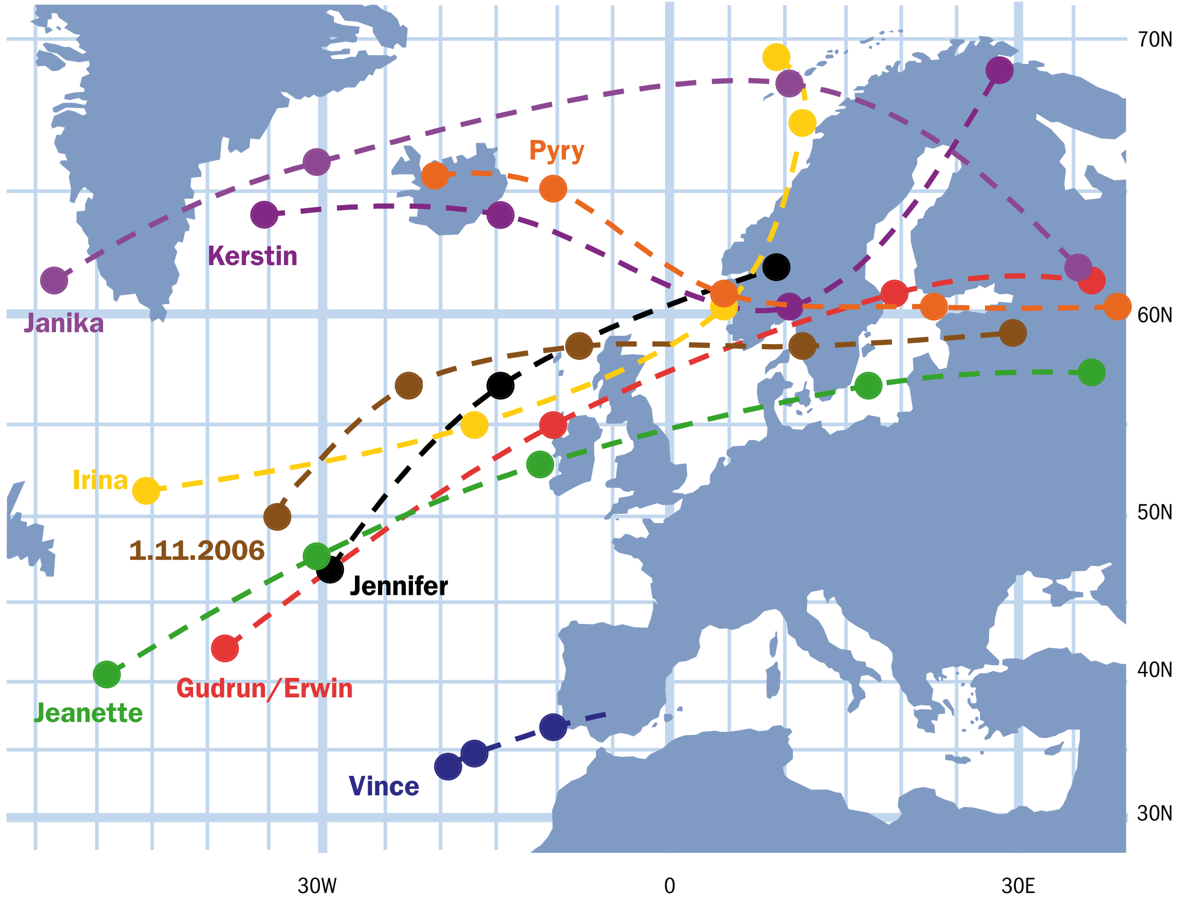
TradeWind selected a few moving low pressure systems in order to study the effect of wind speeds and changes to wind power production and power transfer changes caused by increasing/decreasing wind power production. The low pressure systems chosen were the storms known as Janika (November 2001), Jennifer (January 2002) and Gudrun/Erwin (January 2005). The trajectories of these storms are depicted in Figure 13. As the storms passed over Europe, they were studied, using wind power capacity scenarios for 2015.

The effect of deep low pressure systems passing was less noticeable and less straightforward than expected by the TradeWind experts. The analysis carried out led to the following explanations:

- The time scale of moving low pressure systems is in the same order of magnitude as diurnal load variation. It is hence difficult to detect the effect of moving low pressure systems on cross-border transmission.
- Wind power capacity and its absolute production variations according to the Medium scenario and the prediction for installed wind power in 2015 as used in these calculations, are relatively small compared to the national load and its variations (with the exception of regions with high wind energy penetrations such as in Germany and Denmark)
- In part, wind power replaces forms of domestic generation and so not all cross-border power exchange is affected.
- Cross-border connections might be and remain congested despite wind power. In this case, moving low pressure systems have no impact on the cross-border transmission itself, only on the severity of the congestion.

The analysis and results in this section illustrate that when studying aggregated wind power production from a large area, deciding whether a dip in the production is caused by storm-induced wind farm shut-downs is not always a straightforward task. In several cases, wind farms were shut down only in one part of the country or region. Moreover, part of the reduction in production was caused by basic variability due to decreasing wind speeds.

FIGURE [13]: **Routes of selected low pressures. Dot indicates daily position of the centre of the low pressure.**



4.5 Summary

The impact of wind power on electricity exchanges and cross-border congestion was studied for all TradeWind scenarios by using a flow-based market model. The model represents the European power system as a single market, and cross-border flow is restricted by individual tie-line capacities and NTC values. The analysis carried out looks both at the duration and the severity of the congestion, measured by a line or by NTC “sensitivity value” (the marginal price of the associated constraint).

The simulations identified that many bottleneck situations are independent of the wind capacity scenario, but that they change significantly for the different simulation years. The effects vary according to the national scenarios used for load growth and the development of other types of power generation. The sense

Source: EWEA/Dervaux

of the impact is not always uniform: according to the simulations, increasing wind power capacity does not necessarily entail an increase in congestion on specific interconnectors.

For the simulation years 2008, 2010 and 2015, installed wind power capacity generally has a low impact on congestion. For the later simulation years (2020 and 2030) increased wind integration has a greater impact on congestion, especially between France and Spain, Switzerland, Belgium and GB; GB and Ireland; Germany and Austria; Sweden and Finland, Poland and Germany and Greece and Bulgaria.

Wind power prediction errors have an impact on the hourly cross-border power flow. The results of the simulations indicate that most of the time the deviations between the actual and predicted power flow fall within 20% of line capacity. Obviously, for some cross-border connections, this can increase the severity of congestion.

The effect of moving weather fronts, especially storms, on interactions between wind power production and cross-border power flows, was found to be less noticeable and consequently less straightforward than expected. Several reasons for this have been identified. Firstly, the time scales of moving low pressure systems and of the diurnal load variation are in the same order of magnitude. It is hence difficult to detect the effect of moving low pressure systems on cross-border transmission. Secondly, the wind power capacity, and hence the absolute production variations, are still relatively small compared to national loads and their variations, with the exception of a few regions with high wind energy penetrations. Thirdly, wind power partly replaces other types of domestic power generation and therefore does not replace all power exchange, and in addition cross-border connections might be and remain congested despite the wind power.

Although the simulation results imply that even large changes in wind power production do not significantly affect cross-border transmission at European scale, this conclusion should not be generalised. More detailed simulations need to be carried out to study in a short time scale wind power variations and their influence on power transmission, locally and within small clusters of countries. For this purpose, dedicated simulation models that use wind speed data of higher resolution in time and space are needed. Studies should be done also at higher wind power penetration levels than covered in this project.

Source: Stiftung Offshore Windenergie

Source: EWEA/Winter

5. Cross-border transmission upgrade with increasing wind power penetration

5.1 General

This chapter analyses grid reinforcements that could potentially increase cross-border transmission capacity. It looks at different years up to 2030 using the three different wind integration scenarios (Low, Medium and High). The upgrades are assessed as to how they could help the EU transmission network accommodate future onshore and offshore wind power capacities, and on how they could utilise the continental-wide smoothening effects of wind power. The various solutions, and the benefits they offer, are also evaluated in economic terms.

5.2 Present situation and existing upgrade plans

5.2.1 NEED FOR UPGRADE BOTH FOR BETTER MARKET FUNCTIONING AND WIND POWER INTEGRATION

Market, technology and the environment hold fundamental changes and challenges for the European transmission and distribution networks. One of the major drivers is the emerging internal electricity market in Europe, which requires enough transport capacities between regions and countries to enable effective competition in the power market. In addition, the specific nature of wind power as a distributed and variable-output type of generation necessitates specific investments in national and transnational infrastructure, as well as the implementation of new technology and grid management concepts [20]. Being able to integrate the significant offshore wind power resource is an additional challenge for the European network.

In their assessment of the 2008 situation European TSOs concluded [21] that the current transmission network is capable of handling the wind power currently installed. According to the study, TSOs are strengthening their networks and are implementing operational procedures and control systems that seek to maximise the usable capacity of the existing assets. They conclude that further capacity and strengthening of the European network will be required to integrate larger amounts of wind power.

TradeWind has made an initial assessment of significant interconnectors – both planned and deemed necessary – in Europe that would support both market functioning and wind power [22]. The suggested list of interconnectors has also been used as guidance for the grid upgrade scenarios (see Section 5.3.2).

5.2.2 EXISTING UPGRADE PLANS AND SUPPORTING FRAMEWORKS

Virtually every continental European country claims to have plans to upgrade its transmission network. Not only are AC overhead lines being built and planned, so are submarine HVDC links across long distances. The large amount of transmission projects in the pipeline is another indicator that the grid within Europe is at its limits and needs to be immediately upgraded.

The UCTE 2008 Transmission Development plan [23] lists many projects in all the sub-regions. The Nordel area's planned developments are summarised in its Master Plan [24].

The plans for grid upgrades in view of future wind power capacities are backed up by national and international system studies. The EWIS study looks at grid reinforcements in view of future wind power capacities,(k) and aims to make concrete recommendations. Specific national studies for network upgrades in view of wind power are reported in the IEA Task 25 for several European countries [25].

Investigating large-scale grid plans in Europe such as the MedRing(l) or European overlay grids reaching out to North Africa was outside the scope of TradeWind.

In recent years, the idea of constructing a dedicated offshore transmission grid has been put forward several times. Because of the prominent concentration of planned offshore wind farms in the North Sea and the Baltic Sea, a transnational offshore grid at first would start in those areas. However, in proposals such as made by the wind farm developer Airtricity the offshore grid has branches reaching to Ireland, France and Spain. A transnational grid provides multiple functionalities and benefits, which is illustrated by the fact that various stakeholders, including TSOs are promoting the idea. Such a grid would not only provide grid access to remote offshore wind farm sites, but would also provide additional interconnection capacity to improve the trade of electricity between markets. It would assist in smoothing the geographically distributed output of the connected wind farms [26]. The utilisation of HVDC technology for such a grid looks very attractive because it offers the controllability needed to optimally share the network for the functions of wind power and electricity trade. This report (see Section 5.3.5) explores possible offshore grid configurations.

Transmission network upgrades all over Europe, especially on critical transmission paths, have been promoted by the European Commission through the TEN-E programme (Trans-European Networks for Electricity).(m) More recently, this effort has been supported by appointing European Coordinators to help to speed up the realisation of projects considered of critical importance for Europe. Provision of transmission to offshore wind power development in Europe is one of these priorities and a specific coordinator [27] has been appointed for the task of speeding up the necessary transmission upgrade.

5.3 Assessment of economic benefits of network upgrades with increasing wind power

5.3.1 GENERAL

The assessments of the transmission network upgrades comprise two or more steps. The first step selects new transmission corridors and candidate lines for reinforcements. The second step analyses the operational benefits of the proposed upgrades. New iterations of selections and benefit assessments are performed if needed.

5.3.2 GRID UPGRADES

Grid upgrades are performed in three steps, referred to as Stages 1, 2 and 3. The planned scenarios for new lines and HVDC cables were included in the Stage 1 upgrades. These scenarios were based on grid development information from UCTE, the UK National Grid and Nordel, as well as the list of significant interconnectors identified in a greenpeace study [26]. A set of grid upgrades that were necessary to get a simulated solution without load curtailment were included. This together forms the Stage 1 upgrades (Figure 14 and Table A-3).

For the Stage 2 upgrades a more formal methodology is used. The grid reinforcements are selected by upgrading the ten branches with the highest sensitivity (see WP6 report for further description of the method [28]). The Stage 2 upgrades are assessed only after the Stage 1 reinforcements have been included. Therefore, the analysis performed in this study goes one step further than previous and ongoing studies. Priority interconnections identified by the UCTE and NORDEL development plans or the TEN-E process, for example, are mostly included as part of the Stage 1 upgrades in our study. The Stage 2 upgrades are identified in Figure 15 and Table A-4.

(k) Available at www.wind-integration.eu

(l) The Mediterranean electric ring project was launched in February 2001. The programme aims to build connections between national networks in the Mediterranean area and between the Mediterranean area and the EU. It was completed in June 2003.

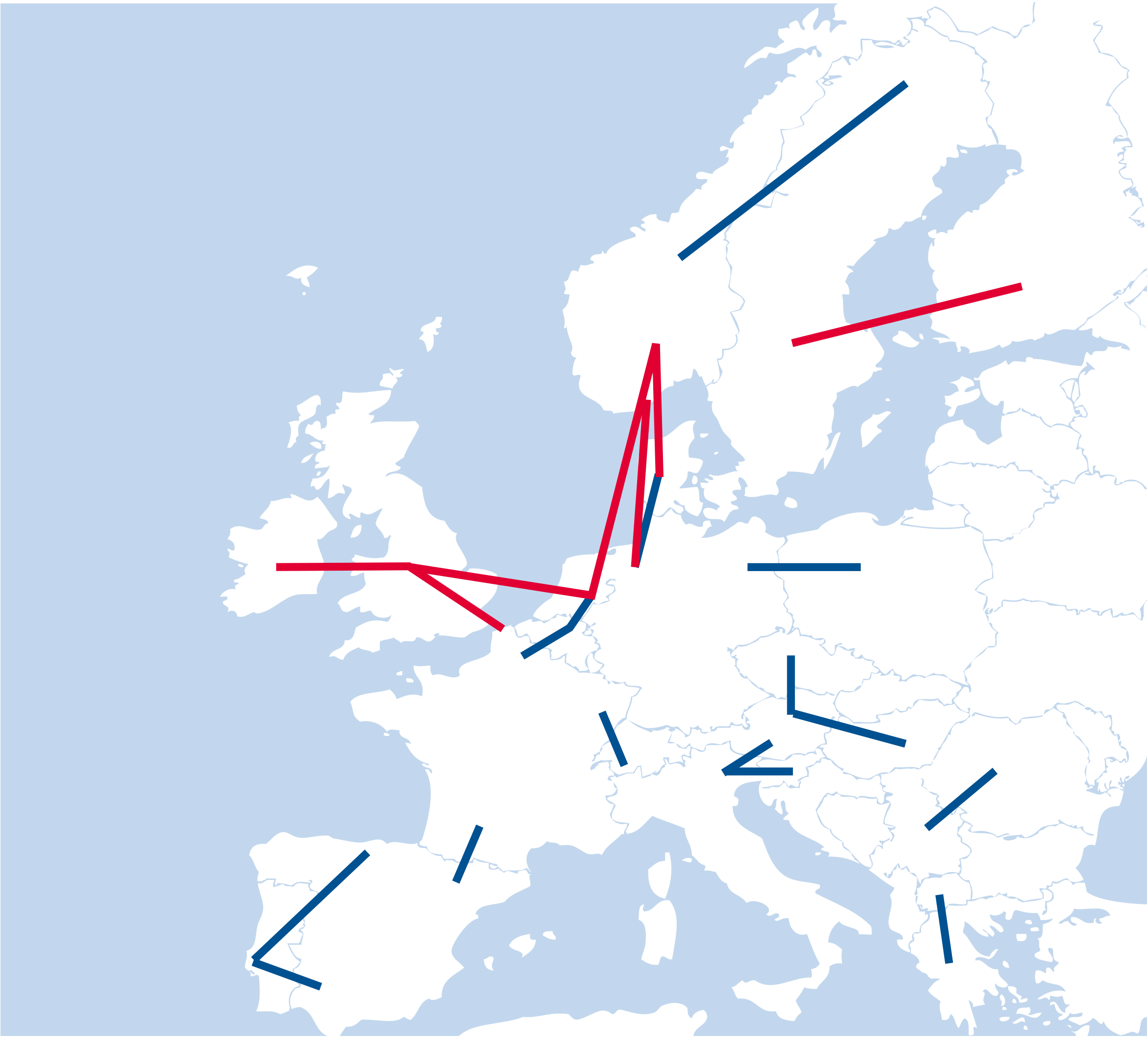
(m) Available at http://ec.europa.eu/energy/infrastructure/tent_e/ten_e_en.htm

A Stage 3 grid upgrade was performed only for the 2030 scenario. The procedure for identifying the Stage 3 upgrades was the same as for Stage 2. In other words, the ten branches with the highest sensitivities were upgraded. The Stage 3 reinforcements were performed in order to assess possible reductions in operating costs through grid upgrades beyond Stage 2. The Stage 3 upgrades are specified in Table A-5.

5.3.3 METHOD OF COST-BENEFIT EVALUATION OF ADDITIONAL TRANSMISSION

The additional system operating costs linked to transmission constraints are called “bottleneck costs” and in part represent the socio-economic costs of not having sufficient transmission capacity. The operating cost in this study includes fuel, emissions, and operation and maintenance costs, but excludes the costs of starting and stopping generators and transmission losses. The benefits of grid upgrades were assessed by calculating the total reduction in operating costs due to transmission upgrades (reduction in bottleneck costs). Other benefits of transmission upgrades, such as reduction in power loss, less need for on-line reserves, lower start-up costs, were not considered. Thus the benefits identified here can be seen as a conservative estimate.

FIGURE [14]: **Stage 1 grid upgrades. Red: HVDC connections. Blue: AC connections.**




Source: Iberdrola

There are two main factors that influence the assessment of benefits related to wind power and transmission capacity. On the one hand, wind energy, by nature being a free but not storable source of energy, must bid into the electricity market at almost zero marginal cost. Thus, when analysing its impact on operational costs, wind will always help reduce costs because it replaces other forms of power generation that have higher marginal costs. On the other hand, wind power - as a variable source of energy often generated far away from load centres - can be expected to lead to higher and more frequent transmission congestions. These congestions will in turn lead to a less optimal utilisation of the generation capacity. In other words, cheap generation in one area must be replaced by more expensive generation in another area due to transmission limitations.

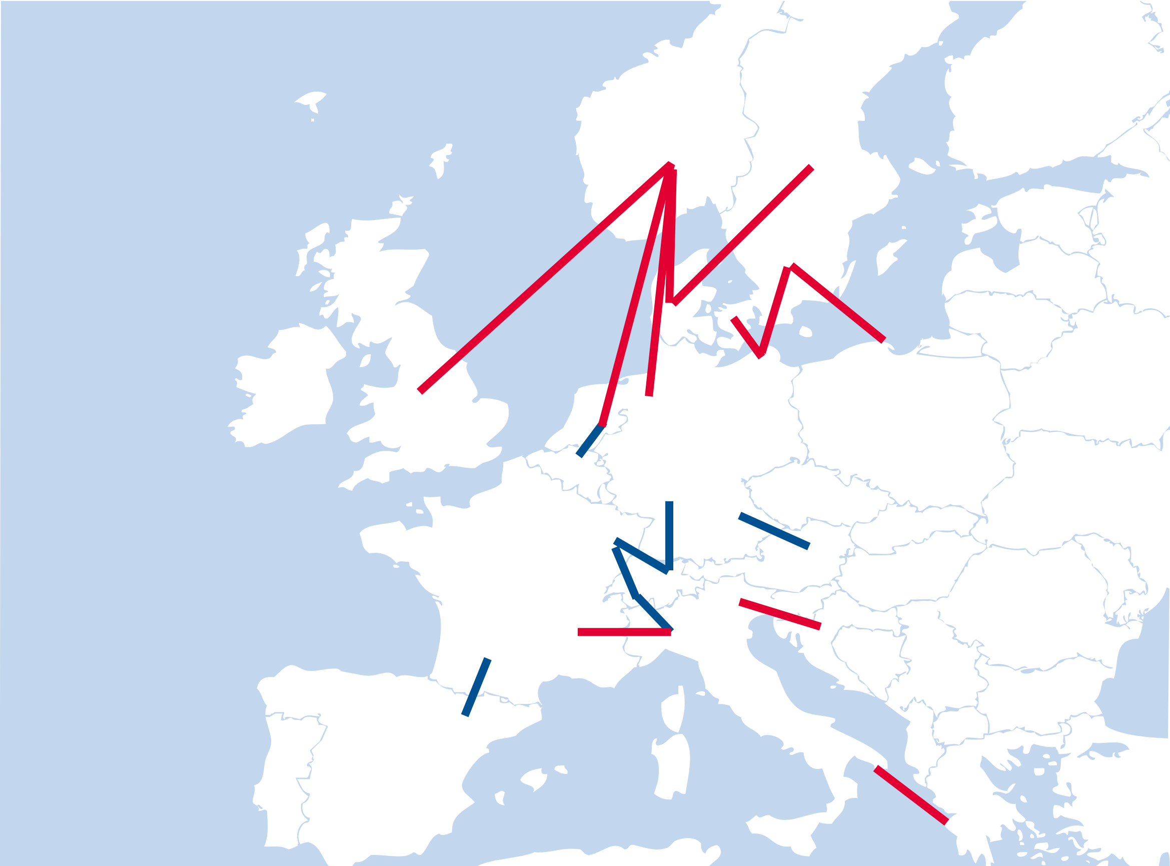
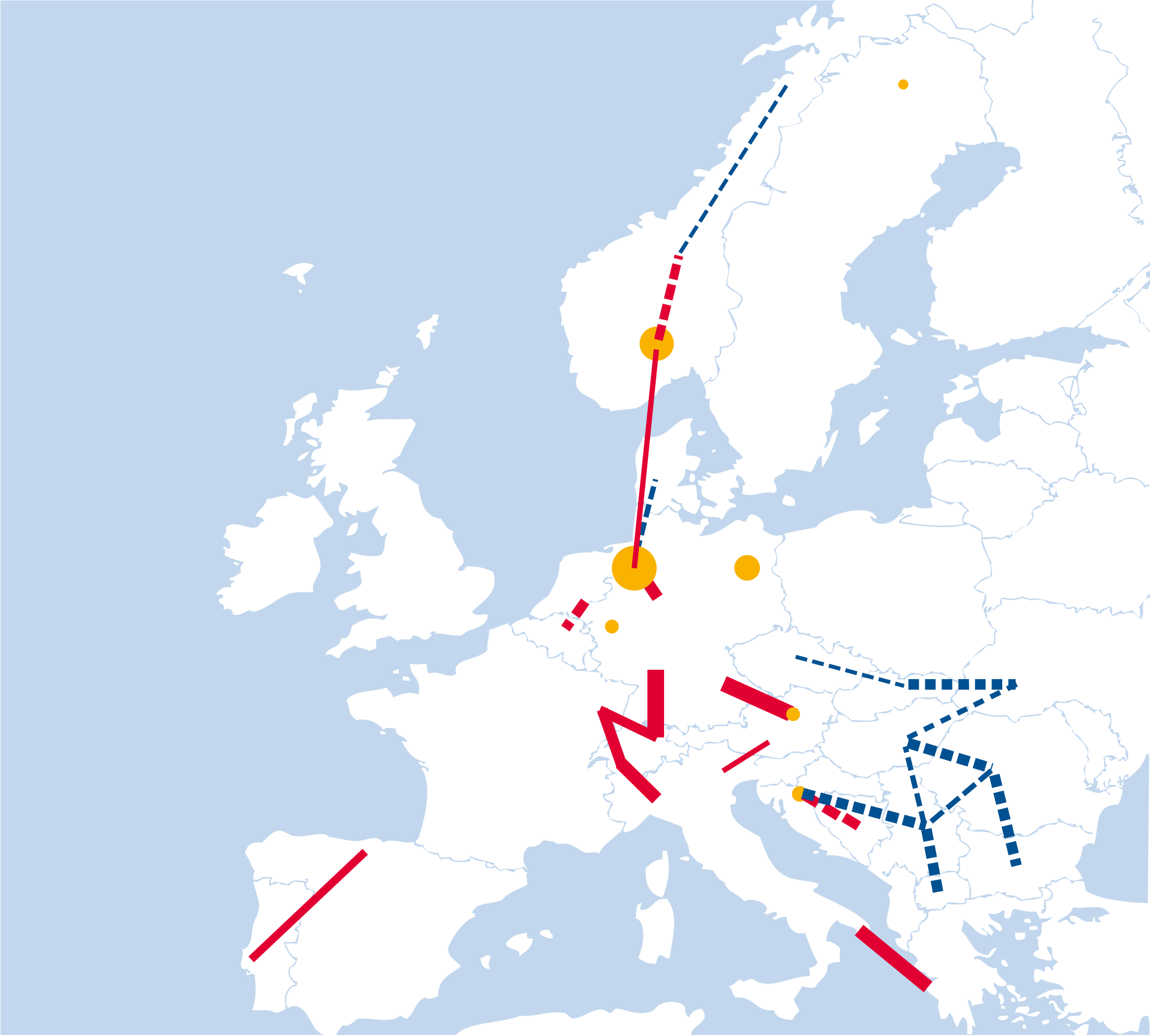


FIGURE [15]: **Stage 2 and 3 branch reinforcements. Red: HVDC connections. Blue: AC connections .(p)**

FIGURE [16]: **Critical zonal corridors based on sensitivities 2030.**
Red: Lines or HVDC constraints. Dashed: NTC constraints. Yellow: Internal constraints.



In order to make a fair assessment of the benefits, the analyses were carried out with and without wind power in the system, and with and without transmission limitations. The operational costs computed without transmission limitations are called “copper-plate model costs”. The additional operating costs when the transmission system model is included are termed “bottleneck costs”.

5.3.4 ANALYSIS OF ONSHORE GRID REINFORCEMENTS

A number of transmission grid reinforcements were proposed for three different years: 2015, 2020 and 2030 [28]. In this section, we will focus on the 2030 scenario, as it is the most critical with respect to wind integration. The main observation (Figure 16) is that wind energy imposes further grid constraints in the north to south direction, from Scandinavia, through Germany, down to Italy, Greece and Portugal.

The proposed upgrades make a positive impact on the transmission grid's ability to handle the increased wind generation. Looking at the energy flows as depicted in Figure 17 the following main changes can be noted:

- An increased transfer of energy between Scandinavia (Norway) to the GB and further on to Ireland and France.
- That upgrades enable more generation in northern Germany that can be transported south and east. This means there is less generation from thermal plants in southern Germany, Italy and Poland.
- Upgrading the link between Greece and Italy enables increased generation and export from Greece.

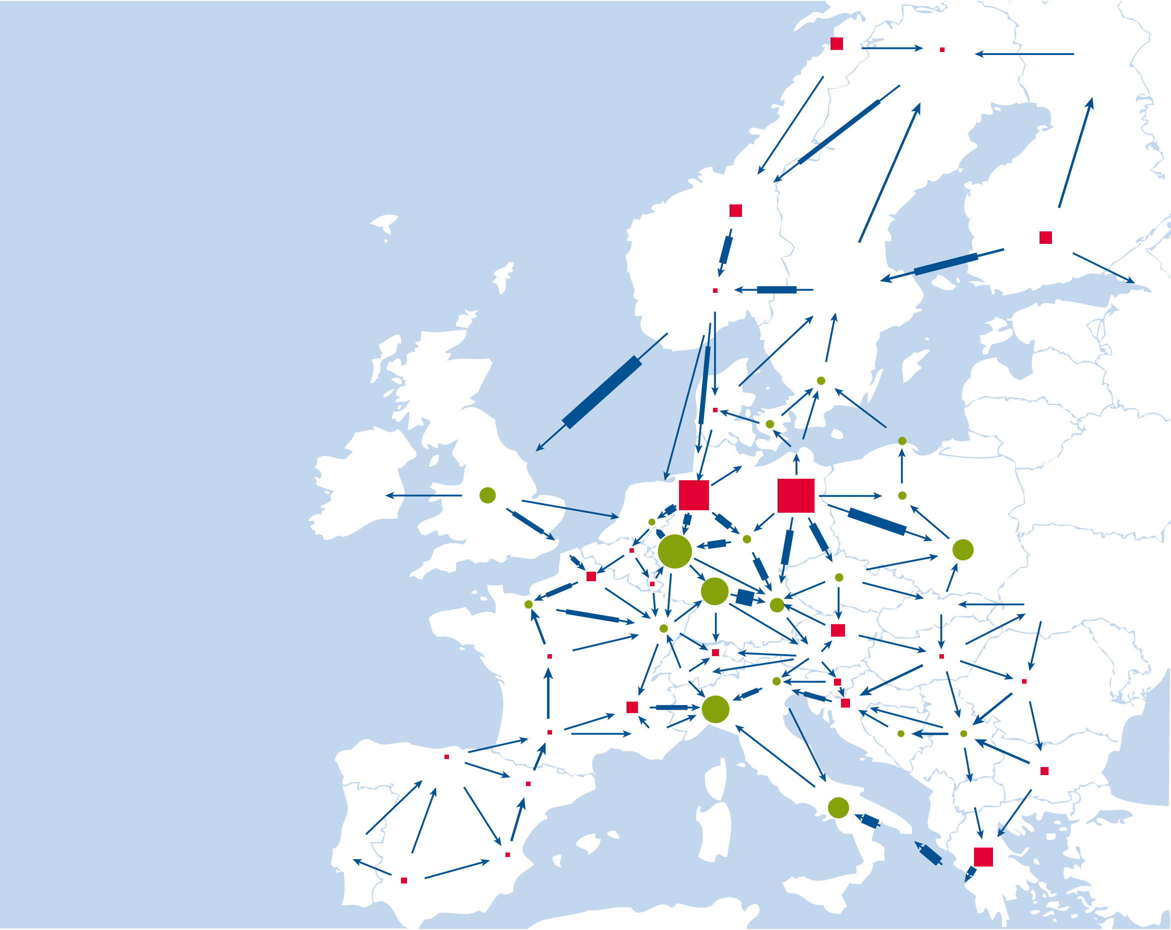
Figure 18 indicates the average operational cost of energy in 2030 for the various wind scenarios (Low, Medium and High) compared to a case without wind power.

A key observation from in Figure 18 is that the reduction in operational costs due to the integration of wind energy is significantly higher than the bottleneck costs. It is thus possible to conclude that the benefits associated with wind generation (such as lower system costs and lower emissions) outweigh the additional costs related to the transmission system limitations for the wind power integration scenarios that are chosen in this study.

However, there are a number of other issues to be taken into account that suggest a more balanced analysis.

For the 2015 and 2020 scenarios, the main observation (see Figure 19) is that the bottleneck costs are relatively small compared to the probable costs of the proposed transmission upgrades. This can be explained by the fact that our scenarios assume an increase in the power load that more or less matches the increased generation from wind in 2015 and 2020. It is likely that this makes the need for transmission upgrades beyond those already planned (Stage 1) more of a local (national) problem than a cross-border pan-European issue. This is confirmed by sensitivity analyses in which attempts were made to include internal transmission constraints. The results showed a significant increase in total bottleneck costs for all cases. However, the relative benefits of the proposed grid upgrades remained largely unchanged both with and without wind power. We can therefore conclude that, according to our analysis, the planned transmission upgrades are well founded.

FIGURE [17]: **Change in net energy flow in 2030 due to Stage 2 reinforcements. Green circles: Reduction in production. Red squares: Increase in production.**

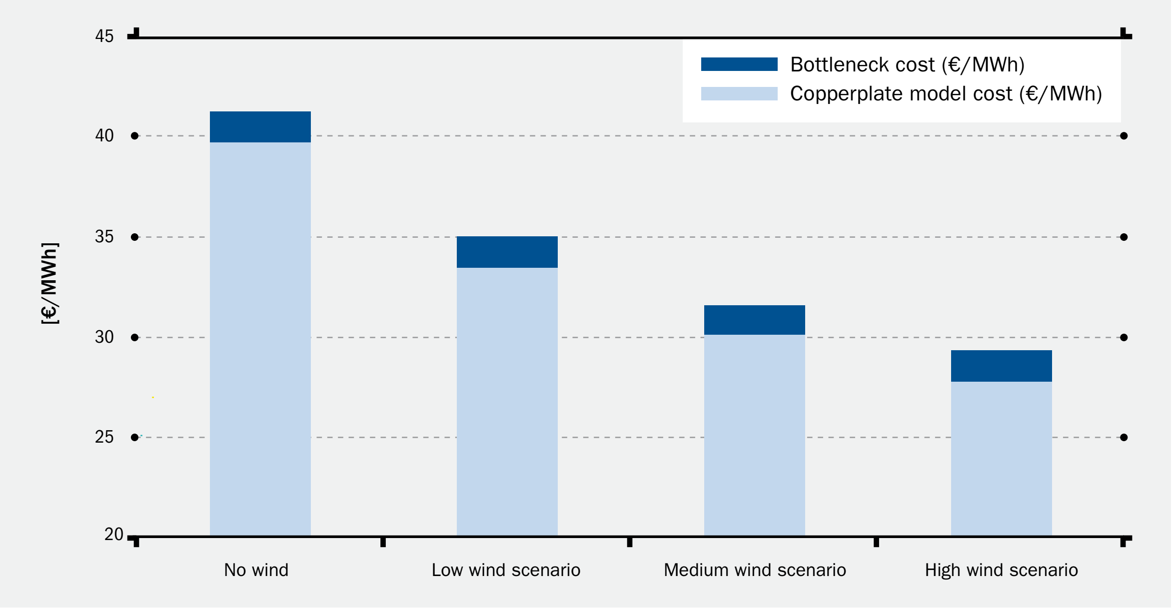


Reductions in operation costs due to the proposed Stage 2 and 3 transmission upgrades are shown in Figure 19. For the 2030 scenario the benefits of transmission upgrades become significantly higher – savings made on operating costs thanks to the proposed Stage 2 upgrades are 870 M€/year and 1500 M€/year for the proposed Stage 3 upgrades. This allows for an average investment cost of € 490 million minimum for each of the 42 projects that were proposed.(q)

In our analyses the benefits are always calculated for the whole European system that is modelled. The question as to who will pay for transmission system upgrades remains. The investment costs, for both wind energy and transmission, are largely at national level. This makes it difficult for transmission system companies to identify profitable transmission development projects, especially cross-border projects. Ways of financing pan-European transmission grid reinforcements must be developed at EU level. This also underlines the need for harmonised planning and authorisation processes (which fully support the TEN-E process).

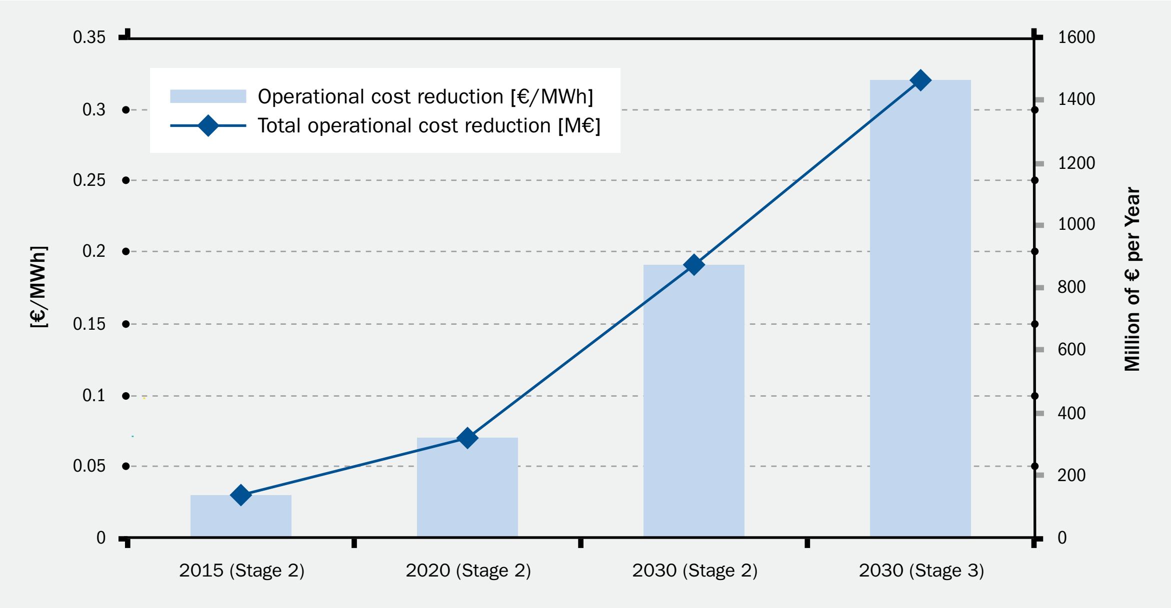
In an attempt to assess the impact of wind energy on the need for transmission upgrades specifically, analyses were performed for each of the scenarios, and also for the scenario that excludes wind power. These analyses show that there is an almost equal need for transmission system upgrades even if very little new wind power capacity is installed. Both wind energy and transmission systems upgrades contribute to reducing these operational costs of power generation. It is therefore important to consider the combined benefits when investment costs (including incentive schemes) are assessed.

FIGURE [18]: **Average cost of energy 2030 scenarios with stage 2 grid upgrades.**



(q) Cost estimates assuming 30 year life and 6 % interest rate on grid investments.

FIGURE [19]: **Reduction in operational costs due to the proposed Stage 2 transmission reinforcements for medium wind scenarios in 2015 and 2020 and Stage 2 and 3 upgrades for the medium wind scenario in 2030.**



5.3.5 OFFSHORE TRANSMISSION GRID OPTIONS

OFFSHORE WIND POWER AND GRID SCENARIOS

The assessment of the scope for offshore grid reinforcement is based on plans for more than 200 future wind farms. The locations of these wind farms in northern Europe are depicted in Figure 20, corresponding to the different TradeWind scenario years. The detailed information about the national scenarios for offshore wind is listed in the WP6 report [28].

	2015 M	2020 M	2030 H
BE	0,5	1,3	3,8
DE	9,8	20,4	30,0
DK	1,0	1,6	3,3
FR	2,0	4,0	4,0
GB	4,8	6,3	33,0
IE	0,3	0,3	0,3
NI	0,1	0,1	0,8
NL	2,0	3,5	20,0
NO	0,1	0,5	7,3
SE	1,8	3,8	11,0
FI	0,6	1,2	3,9
TOTAL	**23,0**	**42,8**	**117,4**

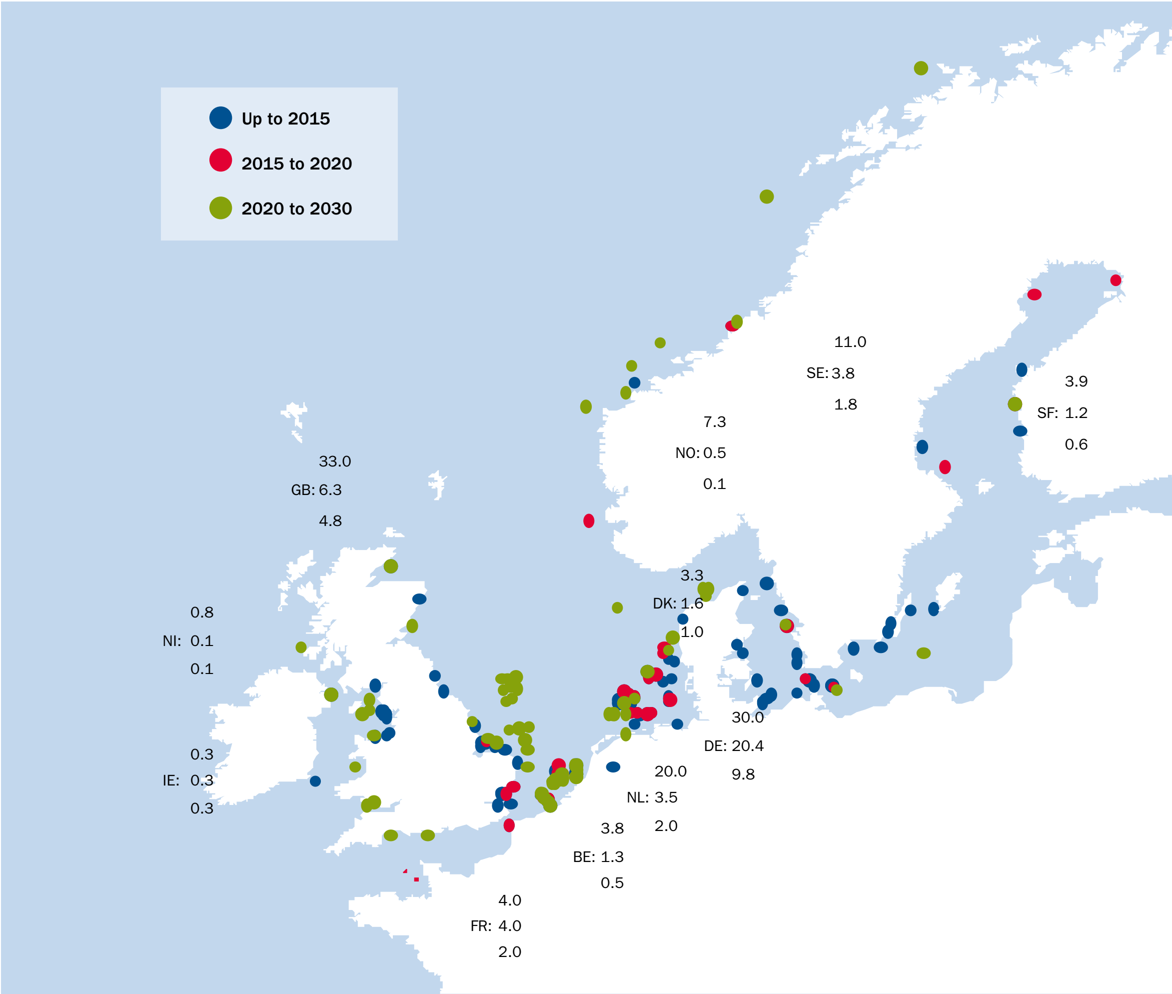
TABLE [4]: **Total installed capacity for the three scenarios.**

For the purpose of the analysis, these wind farm locations have been grouped into several clusters with an assumed common grid connection point.

In order to assess the potential benefits of offshore grid solutions, various attempts were made to design a meshed grid structure in the North Sea and the Baltic Sea. The proposed solutions were then analysed using the TradeWind Power System Simulation Tool, and the results in terms of energy costs and bottleneck costs were compared to the base case solution with radial connections only. Figure 21 shows the base case radial connections of the offshore wind farm together with the sub-sea interconnectors in the North Sea and the Baltic Sea that are included in the grid model for 2030, including the grid upgrade scenarios used in the onshore reinforcement studies above.

Assuming that offshore wind power plants can be linked to each other and to a trans-national HVDC link by sub-sea connectors, it would be possible to design an offshore grid that utilises the cable capacities better than the solution presented in Figure 21. Especially important is the case of north-west Germany, which has been identified as an energy surplus area with high internal congestions in the mainland grid.

FIGURE [20]: **Projected locations of offshore wind farms in northern Europe.**

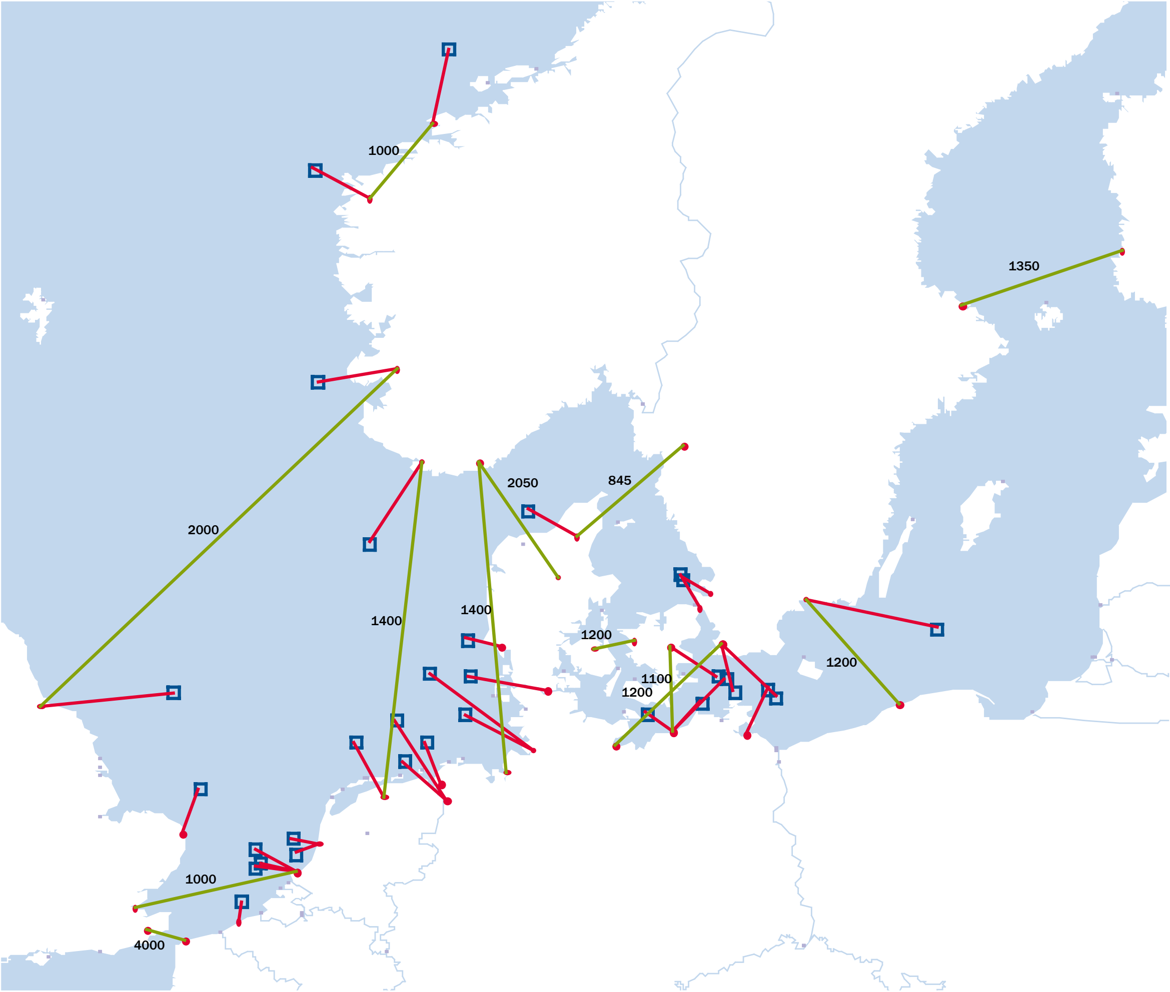


Taking into account that the Netherlands and Belgium will benefit from increased imports, and that Norway has very high amounts of highly controllable hydro power plants, it seems reasonable to study a grid structure which links these countries together. Figure 22 shows such a proposal, which also includes links to west Denmark and the GB. With adequate cable dimensioning, the link from Norway to Germany, via the southernmost Norwegian offshore wind cluster, could be a possible alternative to the NorNed2 cable and the NorGer cable.

In the Baltic Sea, it could be beneficial from a power system operation point of view to link the wind clusters in the Kriegers Flak together, enabling flexibility for transporting higher amounts of offshore wind power to areas with higher prices. Also, such a link would make it possible to trade power effectively between Sweden, east Denmark and Germany in periods with low wind speeds.

The analysis is performed for the High wind scenario for 2030, a scenario which makes full use of the offshore potential of the North Sea and Baltic Sea. The assessments are based on bottleneck costs calculated using a method similar to the one used for onshore grid reinforcements. This is done in order to study the effect of different offshore wind connection alternatives on congestion costs, assuming a baseline scenario with high amounts of onshore wind power in the system.

FIGURE [21]: **Radial connection of offshore wind farms shown together with HVDC interconnectors and their total capacities (green lines).**



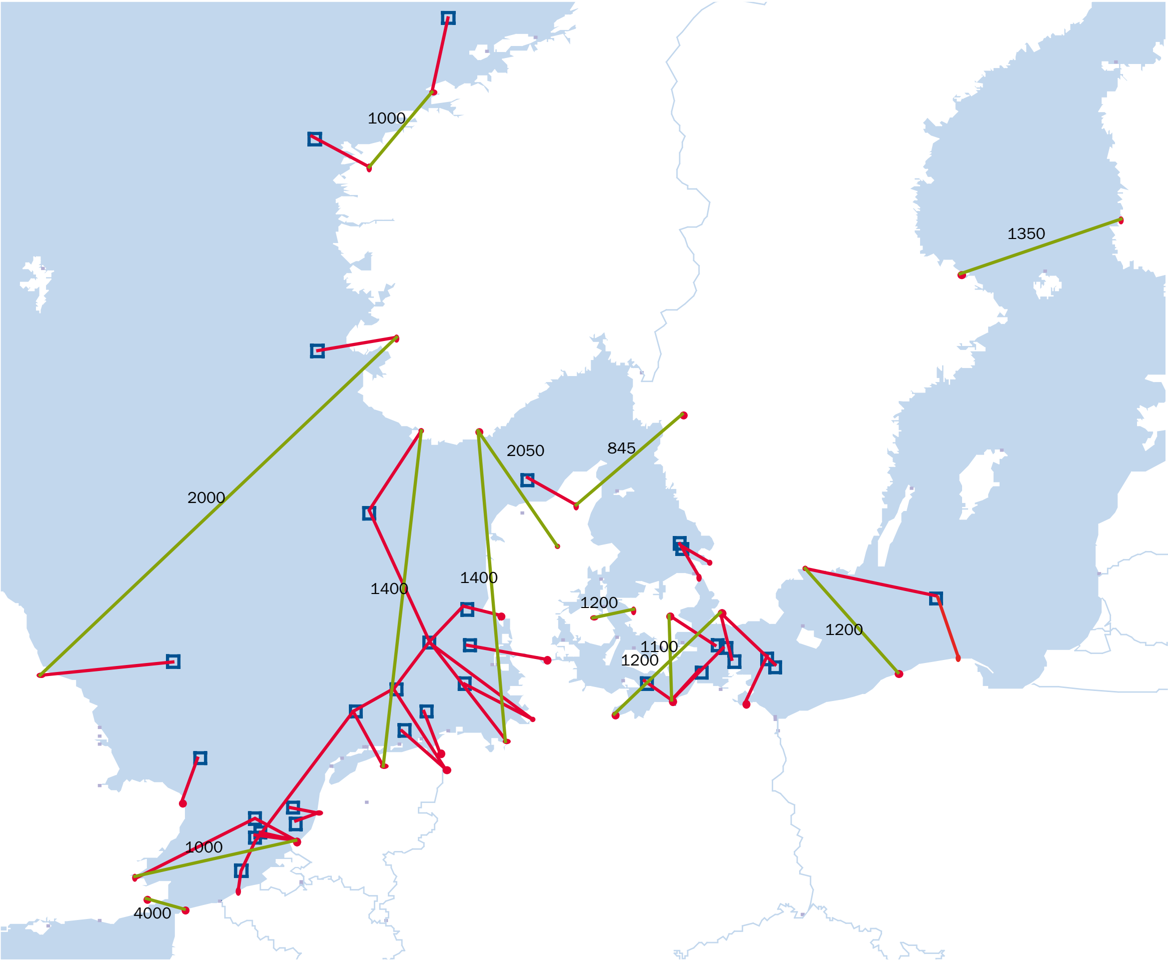
The choice of topology and dimensioning rating of an offshore grid is a complex problem of optimisation, and this project's goal was not to design the optimal grid. Two different design solutions were proposed, denoted "Meshed 1" and "Meshed 2 (Figure 22)", and the results in terms of bottleneck costs are shown in Figure 23. It is noticeable that the meshed offshore grid (Meshed 1) used as first iteration gives higher bottleneck costs than the radial connection alternative. This is simply due to the fact that no attempts were made to optimise the cable dimensioning.

Based on the sensitivity results for the cable capacities, updated cable capacities were proposed and the bottleneck costs of the updated meshed grid (Meshed 2) are remarkably lower than for radial connection. Nevertheless, these bottleneck costs are lower still for the simulation without offshore wind, which clearly indicates that offshore wind power causes significant congestions to the mainland grid.

PRELIMINARY COST-BENEFIT ASSESSMENT OF OFFSHORE GRIDS

The reduced operational cost benefits of the proposed offshore grid solution are given in Table 5 . The benefits are mainly due to the added flexibility introduced when including an HVDC network that links many countries (Norway, Denmark, Germany, the Netherlands, Belgium and the GB in the North Sea and Sweden, Denmark and Germany in the Baltic Sea). HVDC connections are modelled as fully controllable, which makes it possible to avoid bottlenecks in the AC grid when transporting offshore wind power to consumers in areas with an energy deficit or high local generating costs.

FIGURE [22]: **Possible meshed HVDC (meshed 2) connection of offshore wind farms. Dotted lines are HVDC interconnectors. NorNed2 and NorGer are replaced by a HVDC connections between Norwegian and German offshore wind farms.**

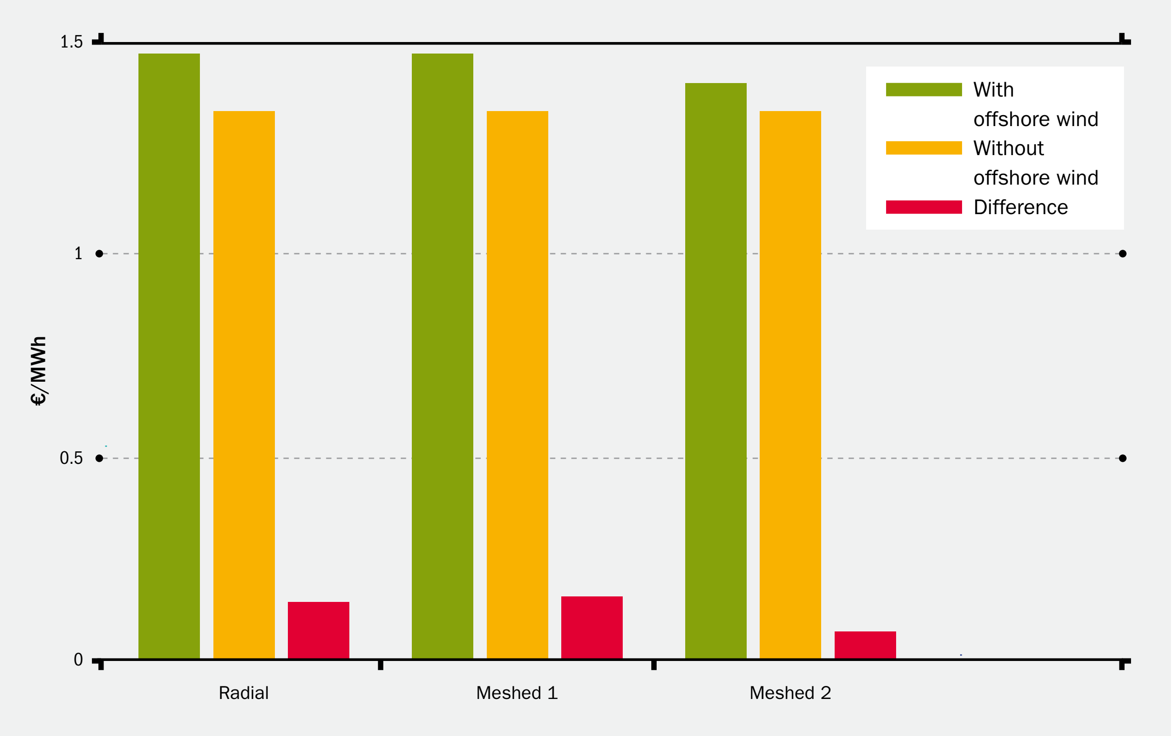


CASE	ANNUAL OPERATING COSTS
Base case Radial connection	131,202
Offshore grid "Meshed 2"	130,876
Reduction in annual operating costs	326

TABLE [5]: **Total power generating cost 2030 High (M €)**

The €326 million difference in total power generating costs can be interpreted as a very conservative measure of the break-even cost for the extra investments needed to realise a meshed offshore network, bearing in mind the limitations of the model in quantifying operating costs. Taking into account factors that are not handled in the model, such as the start-up cost of thermal generators, internal grid constraints and the balancing of wind power, the operational benefits of a meshed offshore grid could very well be significantly higher than estimated by the model. It is also important to notice that the offshore grid structure is by no means optimised in this study. However, to give an idea of how the calculated savings in operational costs compare with the additional investments in the meshed network (with respect to base case radial connection), a simple cost calculation was carried out, assuming cost figures similar to Borkum 2 and oil-platform electrification projects in the North Sea. Based on this data as given in TradeWind WP6 report [28], the added annual offshore grid investment cost is in the range of €300-400 million per year. However, it is important to emphasise that comparison has a

FIGURE [23]: **Bottleneck cost offshore 2030 High wind scenario.**



very limited value, due above all to the fact that added and avoided mainland AC grid reinforcements are not taken into account in the cost calculation. Our main conclusion is that an offshore grid solution may very well be of economic interest when analysed at EU level. It is therefore recommended that this study is followed up with more detailed design and optimisation of offshore grid solutions.

STRONGER MESHED OFFSHORE GRID

In order to effectively integrate high amounts of offshore wind into the power system, it is necessary to upgrade the onshore network. Highly congested mainland connections were observed internally in Germany and Sweden, and connections between Belgium and the Netherlands and between Belgium and France are highly congested. As an alternative to reinforcing mainland connections[r] in these areas further, building stronger offshore grids with direct extensions towards major load centres inland should be considered.

No cost assessment analysis for this type of network concept was carried out, but there are a number of reasons to study extended and more strongly meshed offshore networks, which have HVDC interconnections with much larger capacities:

- The variability of wind energy can best be mitigated on a European scale. For this, the European high-voltage networks must be significantly reinforced in order to create truly "Trans-European Energy Networks"
- Combining the offshore network connections with strong interconnectors is expected to be attractive for the reasons mentioned in par 5.3.5
- Strengthening mainland AC high-voltage networks is very often difficult due to land-use conflicts. By creating a strong 'outer loop' at sea, some mainland network connections may be avoided

Figure 24 gives a conceptual example for such HVDC interconnections in the North Sea, 5 GW rated power per additional connection. The additional connections do not end at the first mainland substation, but extend further into the mainland. The reason for this is to avoid reinforcement of the mainland network near the shore – it may be more attractive to bring the HVDC cables closer to the major load centres. It should, however, be further analysed to what extent network reinforcements can be reduced by this solution.

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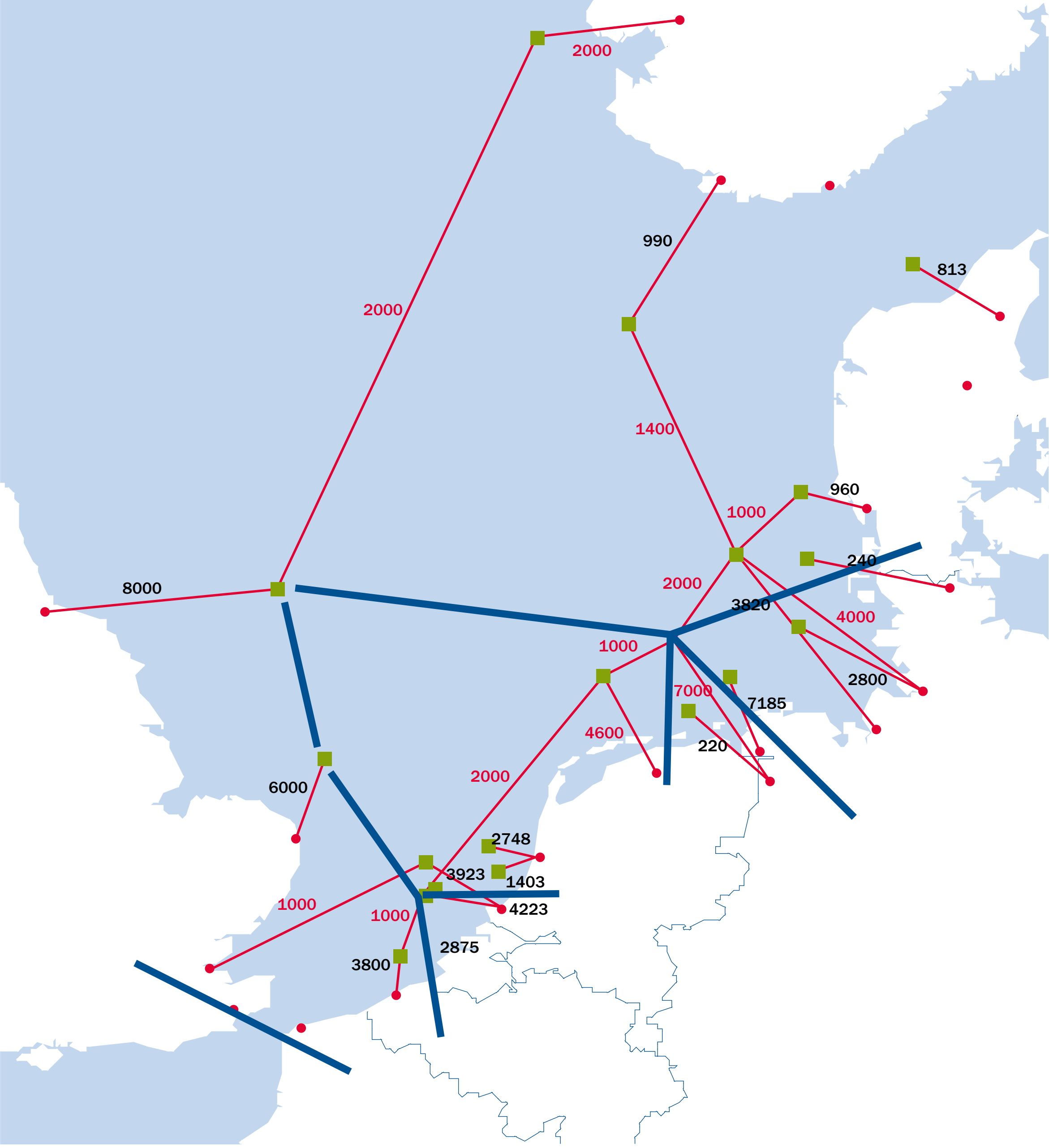
[r] Technology to be developed, or by using parallel cables.

5.4 Power flow control options

Whereas the power flow in DC transmission connections can be controlled, the power flow in AC transmission systems flows according to physical laws, based on the type of network and the distribution of loads and generation. TradeWind examined technologies currently available that can provide power flow control on AC lines, and briefly considered the relevance of such solutions, particularly in relation to large-scale integration of wind power.

FIGURE [24]: **Meshed network on the North Sea, based on Figure 22, with 5,000 MW connections added (bold dark blue lines).**



Obviously, the lack of power flow controllability is only relevant for meshed networks, because there is only one way for the power to flow in radial networks. Still, large transmission systems are normally meshed, as is the case for the large European transmission networks, such as the UCTE system and the Nordel system.

The lack of controllability can sometimes lead to congestion on a possible transmission line while there is still capacity on alternative lines. Since large-scale wind power changes the distribution of the generation in the grid, the growth of wind power can increase the feasibility of AC power flow control. An example of this was shown in Figure 22, where increased wind power generation in central Norway would cause the corridor to Sweden to overload while there was still free capacity on the corridor to south Norway. One option in that case would be to reduce the hydro generation in central Norway when the wind speeds are high, but according to certain studies [29], this would not be an optimal market solution if the AC flow could be controlled. Consequently, it may be feasible to control the flow in certain AC lines, even if it would cost in terms of investment in auxiliary equipment.

Flexible AC Transmission Systems (FACTS) are widely used to enhance the stability in power systems, but some FACTS solutions also support power flow control.

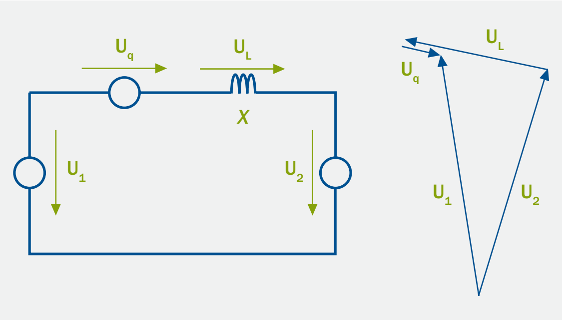


FIGURE [25]: **Principle of AC power flow control**


Source: EWEA/Winter

The principle of AC line power flow control is illustrated in Figure 25, where a transmission line with reactance X connects the two points with voltages $U1$ and $U2$. From network theory it is known that the line power flow is approximately proportional to the angle δ between the voltages on sending and receiving ends of the line. This angle can therefore be changed via a serial Voltage Uq in order to change the flow.

The serial voltage Uq can be provided by different technologies. The most common are phase shift transformers (PST). More flexible (and more costly) options are Thyristor-Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC).

Originally, the idea was to emulate the operation of various power flow control options in the power system simulation tool PSST and thus study possible market benefits that can be obtained by that. This was not possible with the applied tools within the project time frame, but it is certainly an option for future studies. A more approximate approach was therefore taken applying HVDC links providing full power control capabilities, i.e. the effect of power flow control is studied, but not the differences between various technologies (PST, TCSC, SSSC, etc).

Power flow control can ensure that existing transmission lines are utilised to the maximum, which is an important issue, taking into account the public reluctance and long-term project implementation which is normally associated with reinforcement of transmission systems.

5.5 **Summary**

TradeWind investigated what would happen when network upgrades were made and increasing amounts of wind power were available by simulating the power flows and calculating the cost-benefit effects of changes in congestion with and without wind power. The assessment method proved to work well and can be recommended for further studies. Network upgrades were implemented in the model in three stages. The first stage looked at existing plans and studies. By looking at the results of the Stage 1 simulations TradeWind identified reinforcements to be made in Stages 2 and 3. In this way, the analysis goes further than previous or ongoing studies.


Source: http://energypicturesonline.com

It was found that for the scenarios for 2015 and 2020, the savings in system operation costs (bottleneck costs) are relatively small compared to the likely costs of the Stage 1 transmission upgrades. Although it can be concluded from the analysis that the planned transmission upgrades are well-founded, it seems that the need for transmission upgrades beyond known plans (Stage 1) is more of a local problem than a cross-border, pan-European issue. For 2020 and 2030 it was found that the benefits of transmission upgrades become significantly higher, justifying significant investments in transmission infrastructure in the order of €0.5 billion for each of the 42 proposed projects. It is recommended to pursue these investments because of their significant macro-economic profitability.

Topologies of offshore transmission grids were designed and investigated using the TradeWind power flow simulation tool, based on geographical mapping of offshore wind power capacity development in the North and Baltic Seas. A ‘base case’ system of radial connection to the onshore transmission nodes was compared with an interlinked (meshed) HVDC offshore grid linking the countries around the North Sea and the Baltic Sea. A preliminary analysis indicates a better cost-benefit ratio for the meshed grid than for the radial connection solution, and demonstrates that there is an economic case for making the investments. It is recommended that the necessary onshore reinforcements are examined in a further study. This could not be done in the TradeWind project because of the limitations of the available network data. TradeWind proposes a meshed offshore transmission configuration concept linking with direct extensions to major load centres inland. TradeWind has identified the benefits of such a network configuration and recommends making more detailed studies based on this concept.

Power flow control can ensure that existing transmission lines are utilised to the maximum, which is an important issue, taking into account the reluctance and long-term project implementation which is normally associated with reinforcement of transmission systems. This was not possible with the applied tools within the project time frame, but it is certainly an option for future studies.

It is recommended that the work is continued in order to establish an improved network model for all synchronous areas. An updated analysis with improved and validated network models will improve the credibility of the main results from this study.


Source: EWEA/Martin

6. More firm wind power capacity through increased power exchange

6.1 General

TradeWind has looked at wind power's contribution to EU power generation capacity, and at how it is affected when by improved interconnection wind power from different Member States is aggregated, resulting in a smoother and steadier level of wind power production. TradeWind data sets were used to study the effect of enlarging the geographical area on wind power capacity credit. Installed wind power capacities were taken from the Medium wind power scenario for 2020. Wind data was taken from the seven years of Reanalysis data.

6.2 Definition of capacity factor and capacity credit

The terms 'capacity factor' and 'capacity credit' can be easily confused, but they describe very different features of the wind energy generation. The capacity factor is defined as the average power production of a wind plant, relative to rated (installed) capacity. Consequently, the capacity factor of wind power directly reflects the wind potential at the wind plant locations. Calculating the capacity factor during the 100 highest peak load hours, for example, gives an idea of how much wind is available during times of high power demand, and gives an indication of the wind and load correlation. But as the capacity factor does not reflect the fluctuations in wind energy and does not include information about the power system at times of peak demand, it cannot be directly used to calculate the contribution of wind energy to the firm capacity of a country's power system.

Capacity credit(5) (sometimes called capacity value) measures firm wind power capacity and hence the contribution of wind power to generation capacity in the system. In other words, capacity credit measures the contribution of wind power to the adequacy of the power system to meet the peak demand. The capacity credit of wind power is defined as the amount of conventional generation capacity that can be replaced by wind power capacity, while maintaining existing levels of supply security. The capacity credit can be expressed both in absolute terms (MW) and as a percentage of the installed wind power capacity. It is generally known that relative capacity credit is at its highest at low wind energy penetration levels and tails off at higher penetration levels (Figure 26) [31]. At low levels of wind energy penetration [32], the capacity factor of wind power during times of high load is an approximate indication for the capacity credit of wind power. At higher levels of wind energy penetration, certainly those expected for 2020, a probabilistic method should be used to determine the capacity credit.

6.3 Wind power production during peak load hours in Europe

The capacity factor was investigated for UCTE as well as for the whole of Europe including the Nordic countries and GB, assuming the 2020 Medium wind capacity scenario. The countries were grouped according to the main UCTE control zones. When considering the average capacity factor of aggregated wind power during limited time periods of high system load for different groups of countries, some interesting observations can be made.

Taking the 100 highest peak load hours, the calculated capacity factors indicate that the aggregated capacity factor of wind power even in low wind years can be of the order of 20% in UCTE1, 25% for UCTE2 and 4, 13% for UCTE3, 27% for UCTE5 and 30% for Nordic countries. For the whole of UCTE and Europe the average capacity factor of wind power can be of the order of 30% during high load situations.

Table 6 shows how the average capacity factors of aggregated wind power during high load for different zones compare to the average annual capacity factors. For the whole of UCTE and Europe, during high load situations wind power production is 20% more than the long term average.

The following can be concluded from this analysis: (the results can be seen in Table 6 and Figure 27).

- The average wind power production during high load situations is around 30%, when aggregating wind from the whole of the EU, and is 1.2 times higher than the annual capacity factor.
- The results for 2020 are strongly influenced by UCTE2, which represents 50% of the EU installed wind power capacity and contains major markets (Germany, France).
- In nearly all the cases studied, wind power production during peak load hours is higher than the average annual production.
- At low levels of wind energy penetration the capacity factor for wind power during times of high load can be used as a rough indication for the capacity credit of wind power. However at the wind energy penetration level expected for 2020 (with wind power covering 12% of gross electricity demand), the capacity factor should be assessed with a probabilistic method.

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[5] As in principle, the terms capacity credit and capacity value have the same meaning, we will only use the term capacity credit to avoid confusion.

FIGURE [26]: **Germany - Relative and absolute capacity credit of increasing installed capacity and changing wind turbine distribution.**

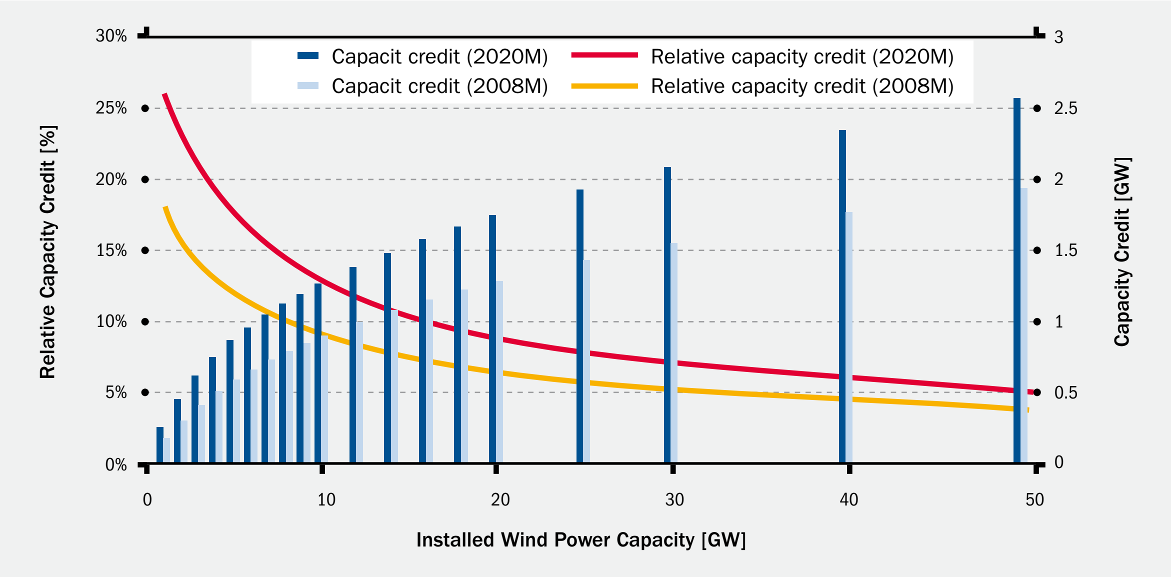
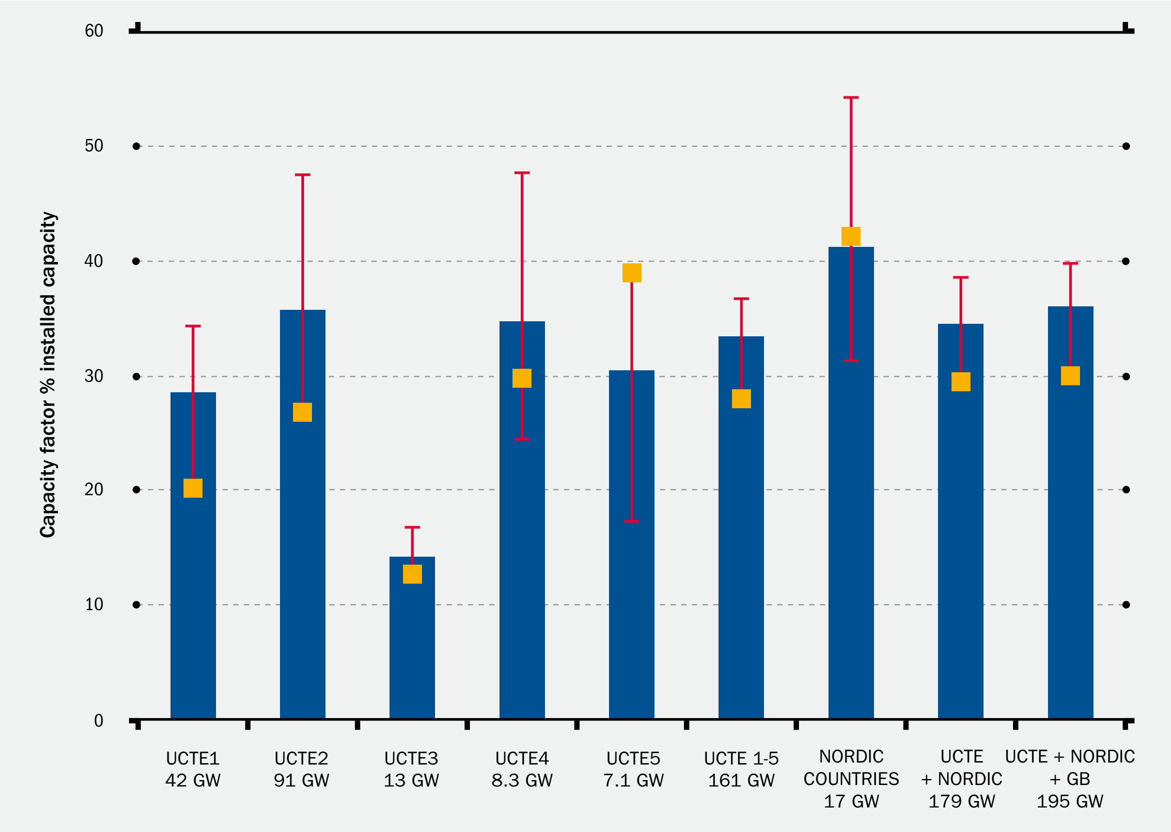


TABLE [6]: **Capacity factors of aggregated wind power averaged over hours of high load and annual averages.**

ZONE	COUNTRIES	CAPACITY FACTOR DURING 100 HIGHEST PEAK LOAD HOURS	ANNUAL CAPACITY FACTOR
UCTE1	PT, ES	20-34 %	25.5 %
UCTE2	FR, LU, BE, NL, DE, CH, AT	27-47 %	23 %
UCTE3	IT, SI, HR	13-17 %	17 %
UCTE4	PL, CZ, SK, HU	24-48 %	23 %
UCTE5	SK, RO, BG, GR	17-39 %	21.5 %
Nordic countries	FI, SE, NO, DK	31-54 %	30.5 %
UCTE (1, 2, 3, 4, 5)		28-37 %	23 %
UCTE + Nordic		29-38 %	24 %
UCTE + Nordic + GB		30-40 %	24 %

FIGURE [27]: **Capacity factor averaged during peak load situations – 100 highest peaks (2020 M Scenario). Average of results over seven years results is presented as a bar, with the range showing as a vertical line. Results from 2006 are marked separately with a square as that year has synchronous wind and load data.**



6.4 Effect of power exchange on capacity credit at EU level

TradeWind determined the EU wide capacity credit and how it is influenced by geographical aggregation through improved power exchange. Therefore, the firm capacity of the system was calculated during higher than average load situations with and without wind power following the recursive probabilistic convolution method [32]. This method gives a level of probability to the availability of each power generation unit in the system at the time of peak load. Wind power 'availability' during peak load is statistically derived from wind power time series analysis during hours where power consumption is high. The method uses the 2,624 hours with the highest load (30 % of the year). The capacity credit of wind power was calculated as the difference between the firm capacity of the system with and without wind energy, maintaining supply security at a level of 99 %.(u)

The capacity credit of wind power for individual countries was calculated from country specific wind energy time series, using seven Reanalysis wind years (2000-2006), and wind power capacity values corresponding to the Medium scenario for 2020.

The final result was considered to be the minimum capacity credit of the seven years. Their average value would have been misleading because the capacity credit is directly linked with system security and only the worst case scenario gives a reliable result. Detailed description of the method is given in the TradeWind WP5 report [33].

The groups of countries were aggregated by adding together the individual country's wind energy time series and scaling down the total, weighted according to the total annual output per country and resulting in a smoothed wind energy time series per individual country.

The results for the 2020 Medium scenario (200 GW, 12 % wind energy penetration) show that aggregating wind energy production from multiple countries strongly increases the capacity credit. The wider the countries are geographically distributed, the higher the resulting capacity credit (Figure 28).

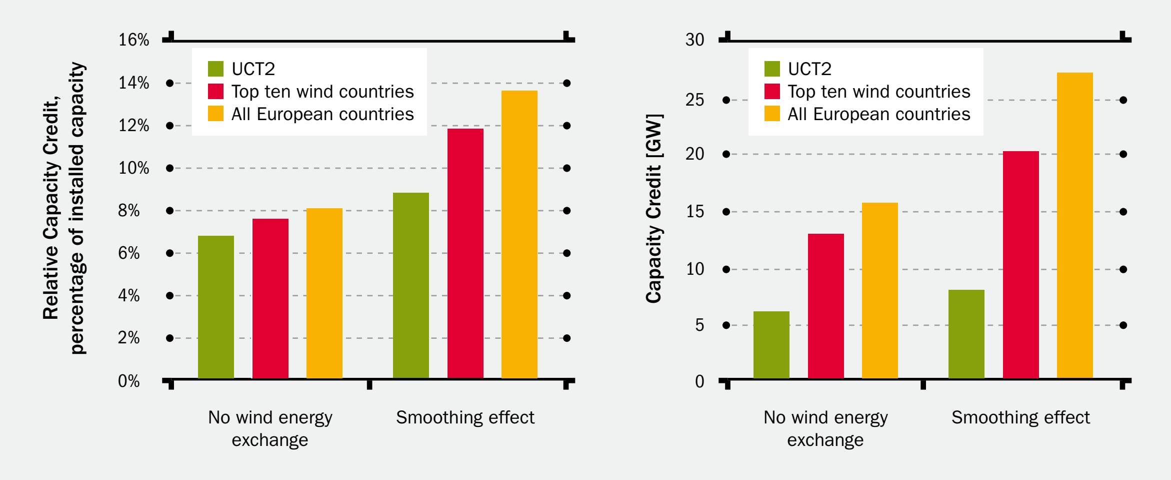
For example, for the ten countries with the highest installed wind energy capacity in 2020 according to the scenario (Germany, Spain, France, the GB, Italy, Portugal, the Netherlands, Sweden, Poland, Denmark), the capacity credit increases by a factor 1.5, namely from 8% (not aggregated) to 12 % (aggregated). Looking at the countries in zone UCTE2, the values are slightly lower and the capacity credit increases from 7 % (not aggregated) to 9 % (aggregated).

The effect of wind power aggregation is the strongest when wind power is shared between all European countries. At EU level without wind energy exchange, the total capacity credit is 8 %, which corresponds to 16 GW of firm power. On the other hand, when one European wind energy production system is distributed across multiple countries according to their individual load profiles, the capacity credit increases by a factor of 1.75 to reach 14 %, which corresponds to 27 GW of firm capacity. It would be pertinent to compare this number to the estimated additional generation capacity needed in Europe 2020 to maintain system adequacy.

Source: Stiftung Offshore-Windenergie

(u) 99 % level of supply security means that in the considered balancing zone the annual peak load cannot be covered without power import from neighbouring zones in one out of 100 cases.

FIGURE [28]: **Increase in the capacity credit in Europe due to wind energy exchange between the countries in the 2020 M Scenario (200 MW, 12 % penetration)**



6.5 Summary

TradeWind used the European wind power time series to calculate the effect of geographical aggregation on wind power's contribution to generation adequacy.

In almost all the cases studied, it was found that wind power generation produces more than average during peak load hours. In almost all cases it was found that wind power generation is higher than average during peak load hours. For the 2020 Medium scenario the countries studied by TradeWind show an average annual wind power capacity factor of 23-25 %. This value increases to 30-40 % when considering the wind power production during the 100 highest peak load situations, which is 20 % higher than the average annual wind power capacity factor. These values are strongly determined by the wind power capacities in UCTE2 (Germany, France).

The probabilistic capacity credit calculation confirms the capacity factor analysis: load and wind energy production are positively correlated, which is beneficial for the capacity credit of wind energy. The results for the 2020 Medium scenario show that aggregating wind energy production from multiple countries strongly increases the capacity credit - and the larger the geographical area the grouped countries represent, the higher the credit is. If no wind energy is exchanged between European countries, the capacity credit in Europe is 8 %, which corresponds to 16 GW. When Europe is calculated as one wind energy production system and wind energy is distributed across many countries according to individual load profiles, the capacity credit almost doubles to a level of 14 %, which corresponds to approximately 27 GW of firm power in the system.

In order to maximise the contribution of wind power to system adequacy, there needs to be sufficient power exchange capacity between the Member States. TradeWind has made a preliminary analysis of the possible opportunities for increasing capacity credit at EU level. Reinforcement of cross border transmission capacity will be beneficial for the capacity credit and system security.

Looking at the figures above, it becomes clear that wind capacity has a significant potential to replace conventional capacity at a high degree of reliability. Hence, there is a need to establish at EU level a harmonised method for calculating the capacity credit of wind power, which can then be used in system adequacy forecasts.


Source: EWEA/Brolet

7. Assessment of electricity market design for high wind power penetrations

7.1 General

7.1.1 OBJECTIVES

For an efficient integration of wind energy into the European energy supply, transmission capacity is essential, but transmission capacity alone is not enough. Along with transmission lines, rules are required that lead to an efficient allocation of these lines that takes into account generation from variable and decentralised generators with limited predictability. In line with the liberalisation of power markets in Europe, these rules are preferably market-based. The political goal is a set of market rules that provides an incentive to the market parties for global minimisation of the costs and emissions of power supply, within the energy economic context in Europe as anticipated for 2020 and beyond.

TradeWind aims to assess power markets in order to show the efficiency of the European power market with a high share of wind power for different market designs and stages of integration.

7.1.2 MARKET PARAMETERS

To a large extent, market barriers to electricity from wind energy are due to imperfect existing markets. Prominent imperfections are the threshold to market access for small and distributed wind power generators or the lack of information about spot market prices in alternative neighbouring markets during the allocation of cross-border capacity, for example. While barriers to small generators may be overcome by aggregation, the lack of information from alternative markets may be overcome by the coupling of national markets with implicit capacity allocation. Examples for market coupling are the Nord Pool market in the Nordic countries and the tri-lateral market coupling between the Netherlands, Belgium and France.

Market barriers to wind power often come from market rules that are badly adapted to that form of power generating technology. Most of the current rules were developed for nationally contained power systems with largely thermal and centrally dispatched generation units. Consequently, they are not ideal for integrating power with variable availability, limited predictability and very low marginal cost – characteristics of wind energy that need to be taken into account in market rules for an efficient integration of wind energy.

7.1.3 APPROACH

The work starts with an inventory of the present situation and recent developments in the European power market. Existing inefficiencies are quantified by analysing the empirical market data. Finally, the sensitivity of market outcomes to market design criteria is assessed through simulations. The market results are quantified by means of consistent market indicators.

7.2 Present situation and developments in the European electricity market

7.2.1 LIBERALISED NATIONAL MARKETS

The liberalisation of the European electricity market aims to create a competitive and truly integrated electricity market in the European Union. The first years of liberalisation were characterised by the opening of national markets for competition.

As a consequence of ownership unbundling of generation, transmission and distribution, genuine utility companies cease to exist. The public obligation of the vertically integrated utility - to keep the lights on by controlling generation, transport and distribution - is no longer valid, and gives way to self-dispatch mechanisms. This means that while the transmission grid is controlled by the TSO, the power plants are dispatched by the market parties.

In order to guarantee grid security, self-dispatch is accompanied by the concept of balancing obligations. Each user of the transmission grid is responsible for keeping his activities neutral with respect to the grid, i.e. to take the responsibility for the equilibrium of injections to and withdrawals from the transmission system within the user's portfolio. As a consequence, grid users nominate a balanced programme to the TSO on a day-ahead basis, with a time resolution between 15 minutes and one hour. Imbalances (violations of the generation-load equilibrium of a particular portfolio) are settled ex-post with the TSO at an imbalance tariff that is unfavourable a compared to market prices. The TSO keeps the responsibility for the balance of its control zone, contributing thus to global system security. The means to do so, namely the reserves, are contracted from market participants able to provide fast regulating power.

Source: Acciona

TradeWind surveyed power market rules in 25 European countries [35]:

- Most countries in the EU have now liberalised their power markets. Two countries – Slovenia and Malta – are seemingly not going to liberalise their markets, while Switzerland, Greece and Hungary are on the way to liberalisation
- Day-ahead power markets work in most countries, although with a low liquidity in some. In terms of trade on the spot market high shares are only observed in the Nordic countries and Spain. In Spain, the volume traded on the day-ahead market is up to 90% of energy consumption. On the Nordic day-ahead market, the volume traded in 2006 represented about 45% of overall consumption. On the other day-ahead markets this share was mostly well below 20%
- Intraday markets exist in a number of countries, but in most cases with a very low liquidity. These markets serve for the final fine-tuning of portfolios shortly before delivery. Therefore, the volumes traded on these markets are mostly much lower than on the day-ahead markets, typically, a few percent of consumption
- The overall organisation of the balancing markets is fairly similar in many countries; nevertheless significant differences do exist on a more detailed level
- Wind power support schemes are very different in the various Member States: feed-in tariffs are most common, followed by green certificates and premium systems. However, substantial differences exist as to how the type of support schemes used by individual Member States, such as a feed-in tariff or a green certificate scheme
- In most countries wind power is prioritised in dispatch. Only in a few countries (Denmark, Finland) is balancing the generation plant owners' own responsibility
- In most countries, wind power is not penalised if expected production is not fulfilled, but again exceptions do exist
- Explicit auctioning is the most common way of allocating cross-border capacities (yearly, monthly, daily). Day-ahead market couplings exist in the Nordic countries, between the Netherlands, Belgium and France, and internally in Italy

The markets of Denmark, France, Germany, the Netherlands and Spain were discussed in depth. The situation in each of these countries is summarised below.

DENMARK

In general the Nordpool market set-up is successful in Denmark, as indicated by a very high share of the total Danish power supply being traded via the power exchange. Denmark has a very high share of wind power in the power system and until now the power system has managed to cope with it. In January 2007, 44% of total power consumption was supplied by wind power in western Denmark. The average balancing cost of € 2/MWh corresponds to approximately 5-7% of the overall costs of wind generated power and, therefore, balancing costs are not considered to be a major barrier for wind power deployment in Denmark.

FRANCE

The French electricity market is a typical example of the European market design. The majority of trade takes place bilaterally, complemented by organised day-ahead trade on Power Exchange. Since May 2007, there has been one intra-day gate per hour. Wind power in France is supported via a feed-in tariff. Wind power does not have to be balanced by the market players.

GERMANY

The German transmission system is operated in four control zones. The TSOs have to publish time series of load, wind power generation, wind power forecasts and cross-border flows on the internet. Wind power in Germany represented 6% of the gross electricity consumption in 2007. At periods of low load, the wind power generation exceeds the load in some of the control zones. Power has to be purchased by the grid operator, who must level out wind's variability. As a consequence, the day-ahead wind power forecast influences the spot market price. Intra-day deviations from the forecast are valued via the balancing mechanism. Wind power does not have to be balanced by the market players.

NETHERLANDS

The wholesale market for electricity is fully liberalised. Various marketplaces exist for electricity, from long-term trading to day-ahead spot market trading. The majority of trade takes place bilaterally. In September 2006, an intraday market was opened. A trilateral market has been established between the Netherlands, Belgium and France to enable implicit auctioning of cross-border transmission capacity. For other interested players, capacity is auctioned on the spot market (day-ahead basis). Wind power needs to be nominated on a day-ahead basis by those responsible for balancing their portfolios. With a high share of wind power in the system, cross-border trade becomes very important, as surplus or shortages of wind power can be exchanged with a much larger pool. Large-scale energy storage could also be added to the system. The necessity and benefits of this are being studied at present in the Energy Island - A inverse pump accumulation station project.

SPAIN

While participation in the spot market used to be mandatory, the day-ahead and intra-day markets are complemented more and more by bilateral contracts. Consequently, prices become easier to predict and more transparent than in the past. Wind power may still have to participate in the day-ahead and intra-day market due to the difficulties of participating in medium-term auctions. Consequently, these markets can be very volatile and have generally lower prices due to their concentration of wind power and run-of-river hydro power. The reserves of wind power needed for balancing have been lower than expected thanks to the extensive use of predictions and the spatial spread of wind farms over different areas.

7.2.2 EUROPEAN INTEGRATION

Up to 2006, all markets in Europe were national markets, with exception of the Nordic market. These markets were characterised by one or few dominant power producers that had emerged from the former utilities and that owned a dominant share of the generation capacity in the countries. New market entrants that owned generation capacity abroad faced the difficulty of transporting variable amounts of power over the borders [39].

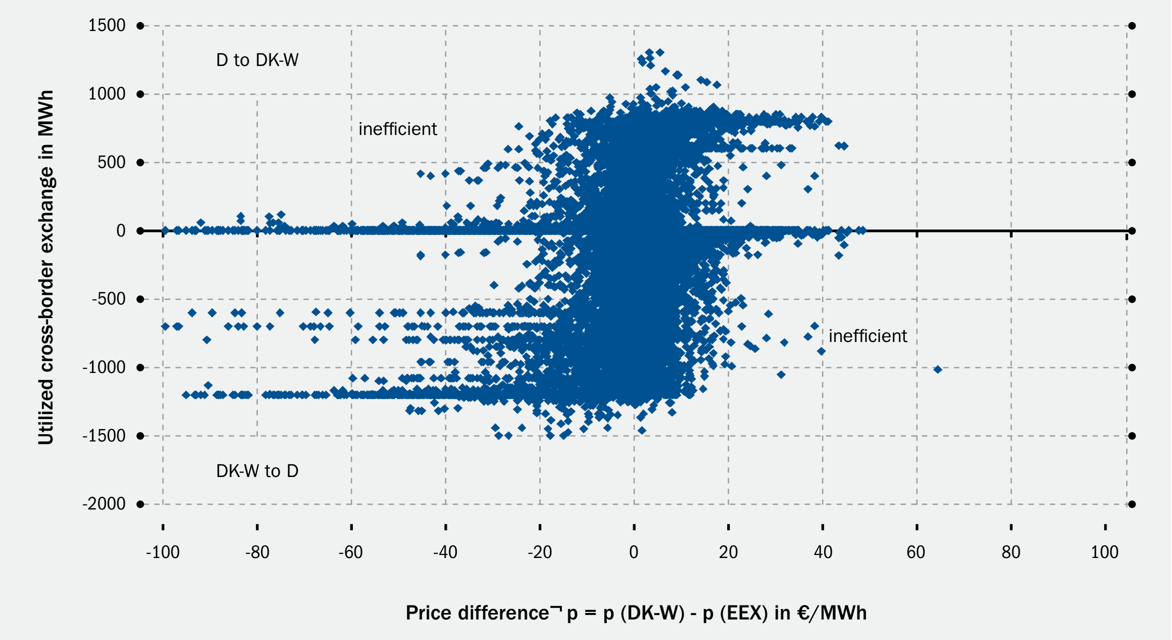
An integrated power market would be made up of different countries. In a perfect market, the market prices would differ between these countries only when the interconnector capacity between the countries was insufficient for arbitrage. Interconnectors would be used based on the evolution of prices on different markets.

While in the past the allocation of interconnector capacity was often not market-based, current mechanisms in Europe are market based, mainly through auctions. Most auctions are explicit, meaning that in order to offer energy on a foreign spot market, a market participant has to separately buy cross-border transfer capacity at the capacity auction, and energy at the concerned spot markets.

Source: EWEA/Winter

Figure 29 shows the correlation of cross-border exchange between Germany and western Denmark, with the price difference between the markets for 2006, when interconnector capacity still used to be allocated at an explicit auction. The available capacity was efficiently used when there was positive price difference and positive capacity, or negative price difference and negative capacity. In total this makes 49 % of all capacity auctions. For 33 % of all capacity auctions, capacity was used inefficiently - namely for bringing power from the high-price to the low-price area. For 18 % of the auctions, no capacity was used, sometimes with a significant price difference between both markets [37].

FIGURE [29]: **Transfer capacity utilised at the German Danish border and price difference between EEX and Elspot (west Denmark); market data for 2006.**



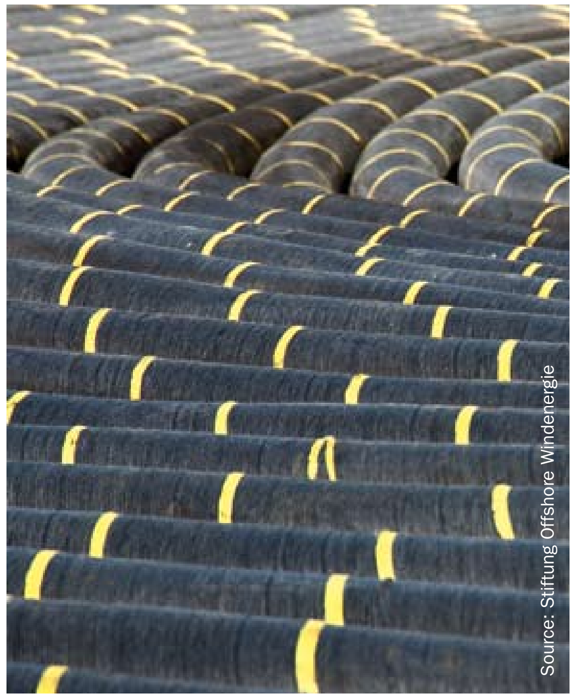
In the last few years, the European integration of power markets has accelerated thanks to the initiative for regional energy markets of the European Regulators' Group for Electricity and Gas (ERGEG). This Regional Initiative pursues the development of seven regional electricity markets, each comprising several national markets.

In order for a power market to be truly competitive, a certain amount of transmission capacity is required within the market regions. Moreover, the legal and regulatory framework must enable an efficient use of the interconnectors between participating countries. This is made possible by market coupling and splitting approaches, leading to an implicit allocation of interconnector capacity: bids and offers from different countries are combined in order to establish a common market price for the region. Whenever an interconnector is congested, the prices on either side cannot converge further and the price difference represents the value of the interconnector for trade. Such implicit auctioning approaches ensure that interconnector capacity is used efficiently [38].

The regional markets as envisioned by the Regional Initiative are listed in Table 7. In this view, the larger countries participate in several regional markets.

Consequently, a market player in one of those countries can choose any of the available market regions for every bid or offer. In practice, this will probably lead to prices in the different regional markets becoming aligned.

The most prominent steps towards regional markets are the Nordpool market and the trilateral market coupling between France, Belgium and the Netherlands. In 2007, Germany joined the Nordpool day-ahead market. Moreover, Germany and Luxemburg plan to merge with the day-ahead trilateral market into the Central West regional electricity market in 2010 (the so-called pentalateral market coupling). Other examples of regional integration are the Irish All-Island market or the Iberic MIBEL.



Source: Stiftung Offshore Windenergie

TABLE [7]: **Seven regional electricity markets as pursued by the ERGEG [39]**

REGION	COUNTRIES	LEAD REGULATOR
Central-West	Belgium, France, Germany, Luxembourg, Netherlands	Belgium
Northern	Denmark, Finland, Germany, Norway, Poland, Sweden	Denmark
GB and Ireland	France, Great Britain, Republic of Ireland, Northern Ireland	Great Britain
Central-South	Austria, France, Germany, Greece, Italy, Slovenia	Italy
Southwest	France, Portugal, Spain	Spain
Central-East	Austria, Czech Republic, Germany, Hungary, Poland, Slovakia, Slovenia	Austria
Baltic	Estonia, Latvia, Lithuania	Latvia

7.3 Method of assessing market efficiency

7.3.1 CHARACTERISTICS AND PARAMETERS

A set of market rules for facilitating an efficient market integration of wind power needs to take into account the characteristic properties of wind energy, namely:

- Wind power is not perfectly predictable. The quality of wind power forecasts increases with a decreasing forecast horizon and with an increasing size of the area for which the forecast is calculated. Along with each forecast, confidence margins can be supplied in order to schedule reserves for compensation of the forecast error
- Wind power is variable with characteristic variations in the range of several hours to a few days. Large intra-hourly variations occur rarely. Wind speed is correlated for short distances but not for long distances in the order of a thousand kilometres and more
- Wind energy requires no fuel. Therefore, its marginal cost is very low and electricity is produced without GHG emissions. Consequently, wind power should be used whenever wind is available. At times of low demand wind power will have to compete with power from bulk load plant, which often cannot adapt their output to fast changing set points

Answering to these properties, we assume that the main parameters that influence the market integration of wind power are:

- The flexibility of rescheduling of dispatch decisions (time dimension)
- The flexibility of the cross-border exchange (time + spatial dimension) and
- The available interconnector capacity (constraints)

The first two parameters are market design parameters. A high flexibility of rescheduling of dispatch decisions will be required when demand and generation are subject to frequent and significant unexpected changes during the day. Flexibility is introduced by generation units with short activation times, e.g., combined cycle gas turbine units or reservoir hydro units. Regarding the second parameter, high flexibility of cross-border exchange is beneficial for market harmonisation. With increasing share of variable generation, flexible cross-border exchange mechanisms contribute to optimising the dispatch on international instead of on national level. As illustrated in Section 7.2, the efficiency of cross-border exchange also depends strongly on the mechanism for capacity allocation. Ideally, capacity is allocated in an implicit way via market coupling mechanisms rather than by an explicit auction. However, since the available market models assume perfect markets, a market simulation including the imperfections of explicit auctioning is not possible.

The third parameter, the available interconnector capacity, is purely technical. It reflects the degree to which the countries are interconnected. Today the interconnector capacity for some important borders is constrained which leads to a limitation of possible exchanges. In the future, grid upgrades and improved congestion management may lead to higher available capacities for cross border exchange. We can, for example, assume the ideal unconstrained case of Europe as a copper plate, or another case where all reinforcements proposed by the Trans-European Networks action will have been realised. This parameter is not a market parameter but rather a boundary condition or constraint for the market simulation work. In a given energy economic context we can define a multitude of cases within these coordinates, defined by flexibility of rescheduling, flexibility of cross-border exchange and the available interconnector capacity (Figure 30). Parametric studies with the different cases show in how far the markets benefit from a better market framework in terms of these three dimensions. The energy economic context is defined by the electricity demand, the generation mix including the overall wind power share and the prices of fossil fuel and CO_2 emission allowances.

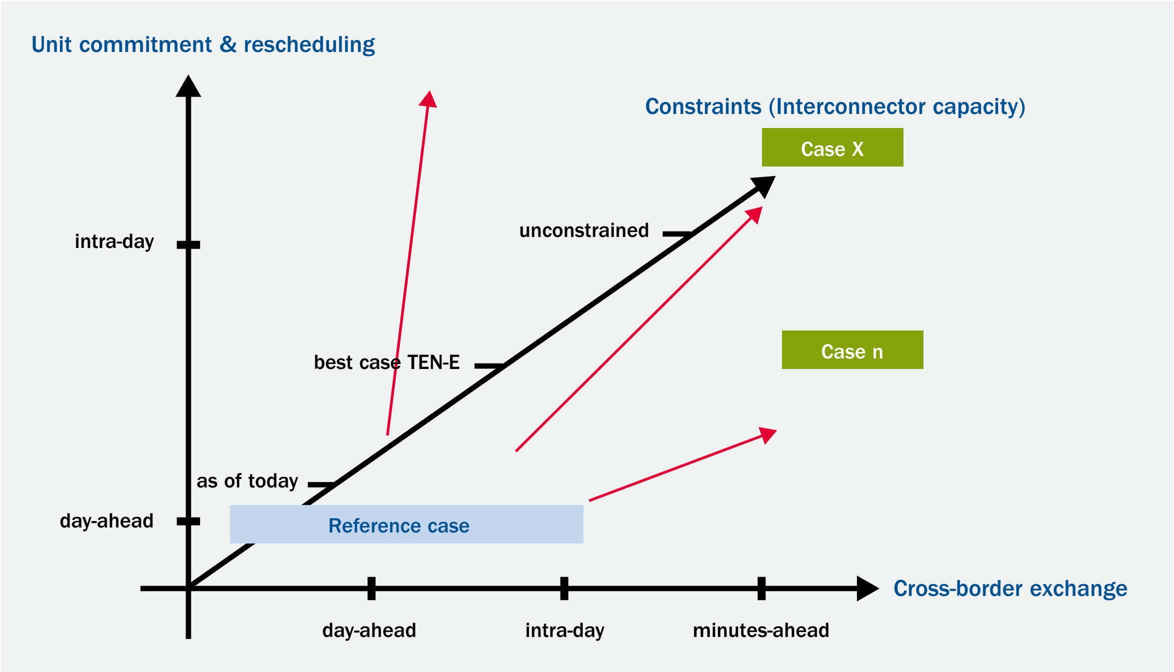
Calculations for the different cases return socioeconomic quantities like the operational cost of power generation, which reflect the value of different cases for society, and technoeconomic quantities that reflect the potential value from the viewpoint of a market participant.

7.3.2 CASES UNDER STUDY

The models of the European power market as developed for the WILMAR planning tool and for PROSYM (see Section 3.6) have been run for different cases.

Source: Siemens

FIGURE [30]: **Cases for market simulation as a function of two criteria and the constraints of interconnector capacity**



The aim is to:

- Simulate the effect of different combinations of market rules
- Calculate macro-economic and techno-economic market indicators based on the results of these simulations

The cases were selected taking into account the specific capabilities of the available simulation tools PROSYM and WILMAR. The different cases are listed in Table 8.

TABLE [8]: **Cases for simulation**

CASE	UNIT COMMITMENT/ RESERVE REQ.	CROSS-BORDER EXCHANGE	NTC CONSTRAINTS	ENERGY ECONOMIC CONTEXT
WILMAR AllDay2020	day ahead rescheduling	day ahead rescheduling	base 2020	scenario 2020, medium wind
WILMAR ExDay2020	intra-day rescheduling	day ahead rescheduling	base 2020	scenario 2020, medium wind
WILMAR AllInt2020	intra-day rescheduling	intra-day rescheduling	base 2020	scenario 2020, medium wind
WILMAR AllIntExRes 2020	intra-day rescheduling	intra-day rescheduling & exchange of reserves	base 2020	scenario 2020, medium wind
WILMAR AllDay2030	day ahead rescheduling	day ahead rescheduling	best 2030	scenario 2030, medium wind
WILMAR ExDay2030	intra-day rescheduling	day ahead rescheduling	best 2030	scenario 2030, medium wind
WILMAR AllInt2030	intra-day rescheduling	intra-day rescheduling	best 2030	scenario 2030, medium wind
WILMAR AllIntExRes 2030	intra-day rescheduling	intra-day rescheduling & exchange of reserves	best 2030	scenario 2030, medium wind
PROSYM d-1 base NTC	Hourly rescheduling	Implicit exchange	base 2020	scenario 2020, medium wind
PROSYM t-3 base NTC	Hourly rescheduling	Implicit exchange	base 2020	scenario 2020, medium wind
PROSYM d-1 best NTC	Hourly rescheduling	Implicit exchange	best 2030	scenario 2020, medium wind
PROSYM t-1 best NTC	Hourly rescheduling	Implicit exchange	best 2030	scenario 2020, medium wind
PROSYM Wind 2008	Hourly rescheduling	Implicit exchange	base 2020	scenario 2020, but wind 2008
PROSYM 200% Fuel Prices	Hourly rescheduling	Implicit exchange	base 2020	scenario 2020 but with doubled oil & gas prices, medium wind
PROSYM Wind must run	Hourly rescheduling	Implicit exchange	base 2020	scenario 2020, medium wind, must-run status for wind power

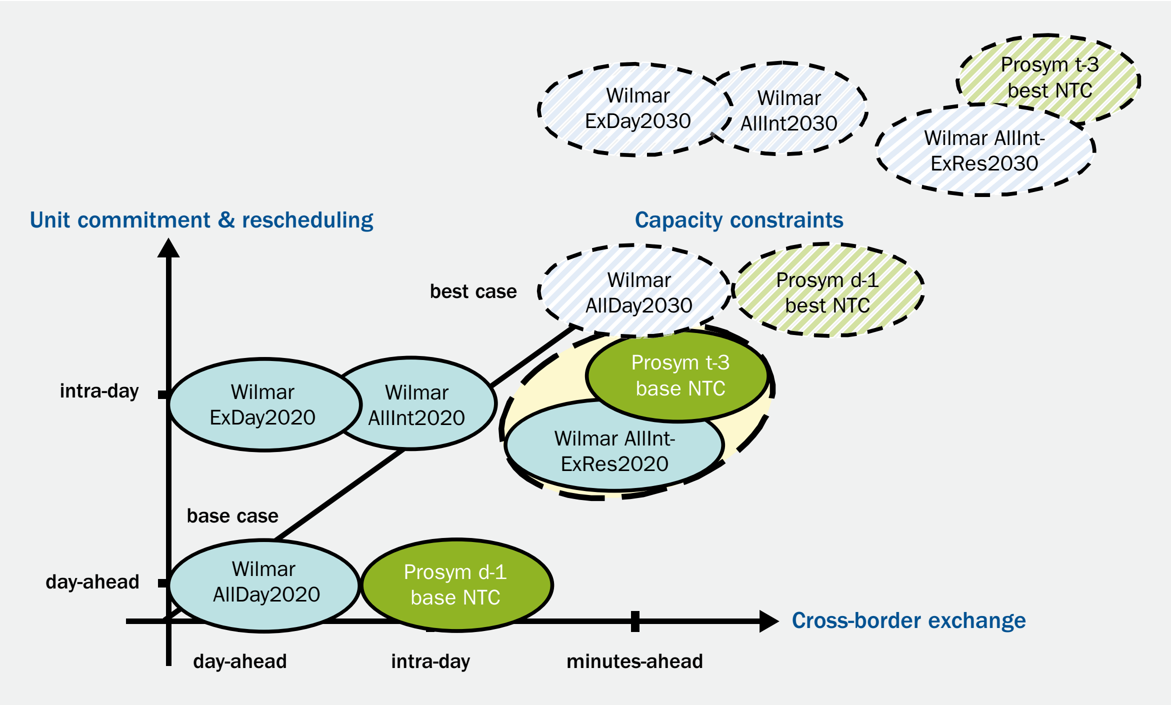
For the two modelling tools, the wind power scenarios, electricity demand, fuel prices, CO_2 costs and transfer capacity values between countries are the same. The assumptions can differ slightly depending on the level of detail with which the generation portfolio is modelled, but also the treatment of reserves and possibilities for rescheduling. The calculations with PROSYM cover 18 European countries with a detailed dataset. Sweden, Finland, Luxemburg, Ireland, the Baltic countries and the countries of east and south-east Europe are not included The calculations with WILMAR cover 25 countries excluding the Baltic countries, Malta and Cyprus. The results from both tools are quantified by a consistent set of indicators.

Figure 31 places the different scenarios that were simulated into a co-ordinate system of spatial dimension, time dimension and technical constraints. The scenarios WILMAR AllIntExRes2020 and PROSYM t-3 Base NTC are comparable and can be considered the most likely for the coming five to ten years. The figure does not show the sensitivity analysis of installed wind power capacity, fuel prices or the possibility of wind power curtailment that were simulated with PROSYM.

The different cases calculated with WILMAR range from inflexible power markets only performing day-ahead scheduling of unit commitment of slow units and power exchange (AllDay in Figure 31), to intra-day rescheduling of unit commitment but still day-ahead scheduling of power exchange (ExDay), to intra-day rescheduling of both unit commitment and power exchange (AllInt), and finally intra-day rescheduling combined with possibility of exchanging reserve power across borders (AllIntExRes). Thereby four cases have been calculated for each of the scenario years 2020 and 2030.

The calculations with PROSYM cover four cases for the target year 2020, characterised by different degrees of connectivity between countries and by differences in gate closure from day-ahead to intra-day, including the possibility for cross-border transfer of reserve power. The gate-closure is reflected by assumptions on the wind power forecast error and the associated requirements for spinning reserves. In addition, sensitivities were checked with PROSYM for the following three parameters: wind energy penetration level, fuel prices, and wind power curtailment strategy.

FIGURE [31]: **Scenarios for market simulation in terms of spatial dimension, flexibility for rescheduling and capacity constraints**



7.4 Evaluation of market efficiency

7.4.1 ENERGY-ECONOMIC CONTEXT

The operational costs of power generation are calculated as the sum of fuel costs including start-up fuel consumption, start-up costs, costs of consuming CO_2 emission allowances, and operation & maintenance costs. Energy not served and reserve deficiencies are not included in these costs but reported separately.

Fuel prices and prices of CO_2 emission allowances, electricity demand and the share of wind power in the system have a direct effect on the system cost. The energy economic context sets the basis from which any further improvement of market rules leads to a further reduction of operational costs of power generation. Based on the market simulations carried out with the WILMAR and PROSYM tools, the main effects of the energy economic context are as follows:

- Wind power as a fuel-free source of power contributes significantly to reducing the operational costs of power generation: assuming the same wind power penetration as in 2008, the cost of power generation in 2020 for the 18 countries modelled with PROSYM would be €119,2 billion. An additional 128 GW of wind power to be installed between 2008 and 2020 yields a reduction of 10% or €10.8 billion per year in 2020. The macro-economic cost savings of wind power replacing conventional sources are then 42€/MWh. This estimate does not take account of investments nor of specific additional costs related to wind power integration such as additional balancing cost and additional incentive costs. Therefore, these savings may be interpreted as being the admissible surplus cost of wind power generation when replacing conventional generation. In other words, from the public support that wind energy receives via quota systems or feed-in tariffs, 42€/MWh is returned to society via the consecutive reduction in operational costs of power generation. Along with this cost reduction, wind power also contributes to a significant reduction of wholesale power prices in the different countries. The actual reduction in average power price due to wind depends strongly on the country. With installed wind power capacity anticipated for 2020 as compared to the installed capacity as of 2008, the price reduction due to wind power varies per country with values not exceeding 16€/MWh

Source: EWEA/Gauthier

- Although wind power capacity between 2020 and 2030 was modelled as increasing by 70 GW, CO_2 emissions increase by 3.6%. This increase in CO_2 is mainly due to the structure of the power generation mix and the increasing electricity demand in the cases modelled. Notably, the applied increase in electricity demand according to Europrog is relatively high in comparison to other sources for the years beyond 2020. In particular, Europrog considers only small improvements in energy efficiency on the long term. These results emphasise the importance of energy efficiency and high CO_2 prices in reducing CO_2 emissions
- With doubled oil and gas prices in 2020 as compared to the European Commission's 2007 baseline scenario, the operational costs of power generation will be about 23% or €25 billion higher. In most countries, 2020 power prices would increase by €20-30/MWh if the fuel prices doubled. Accordingly, the macro-economic value of fuel-free generation in this case would be higher

7.4.2 INTERCONNECTOR CAPACITY

As not much additional cross-border capacity is considered in the best NTC case compared to the base NTC case (see Table 9) and also just for a few countries, there are no significant changes in the import-export balance of most countries. France and Germany will remain net exporters while the Netherlands and Italy will remain net importers of electricity. A significant increase in power exchange can be observed for those countries that today are connected only to a limited extent and for which large increases in interconnection capacity have been assessed in Chapter 5. The difference is especially significant with regard to imports into Italy and into Great Britain.

In conclusion, simulation results show savings with increasing NTC. It is recommended to further investigate the effect of major transmission upgrades as suggested in WP5 in follow-up studies.

Table [9]: **Interconnectors with upgrades assumed for the 2030 best case represented by NTC**

COUNTRIES		**COUNTRY CODES**		**BASE NTC**		**ADDITIONAL NTC** (BEST NTC = BASE NTC + ADDITIONAL NTC)	
Country A	Country B	Country A	Country B	NTC A to B [MW]	NTC B to A [MW]	NTC A to B [MW]	NTC B to A [MW]
Denmark-West	Norway South	DKW	NO	1,450	1,450	600	600
Denmark-West	Denmark-East	DKW	DKE	600	600	600	600
France	Italy	FR	IT	2,650	995	1,000	1,000
France	Great Britain	FR	GB	2,000	2,000	2,000	2,000
Germany	Denmark-East	DE	DKE	550	550	550	550
The Netherlands	Norway South	NL	NO	700	700	700	700

7.4.3 UNIT COMMITMENT AND RESCHEDULING

The following conclusions can be made on the organisation of cross-border exchange, unit commitment and scheduling in international electricity markets:

- In general terms, allowing unit commitment to be re-scheduled as close as possible to real time leads to savings in operational costs of power generation and stable power prices. Not allowing intra-day rescheduling would cause volatile and regularly spiking prices, especially in smaller countries
- Reducing the demand for reserves by accepting wind power forecasts up to three hours before delivery would yield a reduction in system costs of €260 million per year. This cost reduction assumes a perfect market and would be much larger in current market conditions

The impact of different market designs on CO_2 emissions is very small, namely 0.1% to 0.3%. This is because the model for a given target year has to satisfy the same load. Moreover, the generation from wind power and hydropower remains the same, as do the installed capacities of biomass and nuclear power with their very high capacity factors. In total, they have to cover the same amount of load in each market design case because all carbon free production forms are utilised nearly to the maximum amount. Consequently, overall CO_2 emissions mainly depend on whether priority dispatch is given to coal or gas.

7.4.4 FLEXIBLE CROSS-BORDER EXCHANGE

The advantage of flexible markets becomes much more prominent when flexible unit commitment and rescheduling are not only applicable to national markets but also to cross border exchange.

- Allowing for intra-day rescheduling of cross border exchange will lead to savings in system costs of approximately 1%, or in the order of one to €1-2 billion per year compared to day-ahead cross-border exchange
- The cross-border exchange of reserves has a positive but relatively low effect on system costs. In an unbundled market, deviations from the programme are balanced first of all from the portfolios of the parties responsible for balancing. Only afterwards do they put demand on the reserve power markets

In conclusion, the establishment of intra-day markets for cross-border trade is key for market efficiency in Europe. In order to ensure efficient allocation of the interconnectors, they should be allocated directly to the market via implicit auction.

7.5 Summary

In short, the costs of power generation in 2020 to 2030 with a large share of wind power will exhibit:

- A strong sensitivity to fuel prices
- A significant sensitivity to the amount of energy generated from wind

Requirements for a good market design in Europe are:

- Features for intra-day rescheduling of generators and trade on an international level for low system costs and stable prices
- Wide-spread application of implicit auctioning to allocate cross-border capacity (i.e. market coupling, market splitting etc.)
- Application of intra-day wind power forecasting for low reserve requirements
- The availability of sufficient interconnection capacity to enable prices to converge

Wind power curtailment and load shedding are almost inexistent when the market is well designed. An international exchange of reserves is not the first priority for a good market design because the need for reserve power should already be kept low by intra-day rescheduling of power exchange and by intra-day rescheduling of unit commitment and dispatch of units. The main benefit of exchanging reserve power could consist of possible savings from investments in flexible power plants due to reserves being shared across borders.


Source: EWEA/Brolet


Source: Siemens

8. Summary of TradeWind's findings

The TradeWind study on future developments of wind power capacity in the European transmission systems and power markets can be summarised as follows:

Wind power scenarios

Country- and region-specific Low, Medium and High wind power capacity scenarios have been collected for the TradeWind target years up to 2030. Wind power capacity will grow significantly. The speed of offshore development will depend on the expansion of offshore grids, especially in the later scenario years.

The capacity scenario data were combined with the Reanalysis wind speed data to produce hub height and terrain specific wind power time series, with a time step of six hours linearly interpolated to one hour for a grid spanning the whole area of Europe studied. Where necessary, correction factors were applied to get reasonable agreement with observed and expected long-term capacity factors for wind generation in specific areas including the most important wind energy countries and offshore regions.
The TradeWind consortium has exchanged this data set with the EWIS project.

Power flow simulations at European level

TradeWind developed specific methodologies and sets of assumptions in order to simulate the effect of increasing wind power capacity on the European cross border power flows and to make an economic assessment of transmission congestions. Network data for the largest part of Europe (UCTE area) was not available in time from the European TSOs and consequently the TradeWind consortium based its study on data taken from the public domain combined with the knowledge of consortium members. In order to ensure a degree of conformity between the network model used in the study and the actual one received from the TSOs, simulation results were cross checked with respect to location and severity of congestion as well as cross-border energy exchanges enabling an adequate reality check of the TradeWind results.

Generally speaking, the model used in the study gives a good representation of the wind power fluctuations, although due to the low time resolution of the available wind speed data rapid fluctuations are somewhat underestimated. This limits the model's usability for studying the interactions between wind variability and the needs for balancing power.

Calculations made using a more detailed network representation recently obtained from UCTE generally confirm the results. Deviations from the TradeWind results will occur increasingly when simulations are made for future years using more detailed network representations. This is due to the increasing effect of the uncertainty of the location of generators in the network.

The data sets produced by the simulations offer the possibility to do more analysis than carried out by the consortium. Moreover, a better and more detailed network representation for UCTE has now been made available to the consortium, although it has not been used to its full extent due to time constraints. The work reported here therefore does not bear the full conclusions that could potentially have been drawn from the simulations.

Impact of wind power on cross-border power flows and congestions

The impact of wind power on electricity exchange and cross-border congestions has been studied for all TradeWind scenarios with a flow-based market model. The model represents the European power system as a single market, and cross-border flow is restricted by individual tie-line capacities and NTC values. The analysis carried out within TradeWind also looked at the severity of congestion, measured by line loading and marginal price duration curves (line or NTC “sensitivity value”).

The simulations demonstrate that many bottleneck situations occur no matter the wind capacity scenario (Low, Medium or High), but change significantly for the different simulation years. The effects depend heavily on the different national scenarios used for load growth and development of other power generation. The impact is not uniform: more installed wind power capacity does not always result in more congestion occurrences on specific interconnectors according to the simulations.
For the simulations for 2008, 2010 and 2015, wind power generally has a low impact on congestion. For the later simulation years (2020 and 2030) increased wind integration would lead to significantly increased congestion occurrences, especially for the following interconnectors:

- France - Spain
- France - Switzerland
- France - Belgium
- France - Great Britain
- Great Britain - Ireland
- Austria - Germany
- Germany - Sweden
- Sweden - Finland
- Sweden - Poland
- Greece - Bulgaria

Wind power prediction errors have an impact on the hourly cross-border power flow. The results of the simulations indicate that most of the time the deviations between the actual and predicted power flow fall within some 20% of line capacity. Obviously, for some cross-border connections this can increase the severity of congestion. The simulations for 2015 show a limited impact of installed wind power capacity scenarios on the cross-border power flows uncertainty level. Nonetheless, the results indicate that the effect of wind generation forecast errors should be taken up in large scale integration studies.

The effect of weather fronts, especially storms, was found to be less noticeable and less straightforward in terms of wind power production influence in cross-border transmission than expected. TradeWind identified several reasons to this:

- The movement and influence of the low pressure systems are not easy to distinguish from diurnal load variation in most countries and load situations
- The wind power capacities and their absolute production variations are mostly still relatively small compared to national loads and their variations (using the 2015 Medium scenario) possible internal congestions during the rare meteorological events studied were not considered in the analysis
- Wind power partly replaces other domestic generation and only partly replaces power exchange
- Cross-border connections might be congested even without the wind power

Assessment of European transmission infrastructure upgrade for increased wind power

TradeWind investigated the effect of different scenarios for network upgrades with increasing wind power by simulating the power flows and calculating the cost-benefit effects of changes in congestions with and without wind power. Network upgrades were implemented in the model in three stages. The Stage 1 upgrades correspond to existing plans and studies. With the help of the simulations assuming Stage 1 reinforcements, TradeWind identified two progressive stages of reinforcements that would be instrumental for accommodating more wind power. The analysis therefore goes further than previous or ongoing studies.

The assessment method has proven to work well and can be recommended for further studies. It was found that for the scenarios for 2015 and 2020 the savings in system operation costs (bottleneck costs) are relatively small compared to the likely costs of the Stage 1 transmission upgrades. Although it can be concluded from the analysis that the planned transmission upgrades are well founded, it seems that the need for transmission upgrades beyond the known (Stage 1) plans is more of a problem in small areas of some countries than a cross-border pan-European issue. However, for 2020 and 2030 it is found that the benefits of transmission upgrades become significantly greater, justifying significant investments in transmission infrastructure, in the order of an average of €0.5 billion for each of the 42 proposed projects.

Topologies of offshore transmission grids were designed and investigated with the TradeWind power flow simulation tool, based on the geographical mapping of offshore wind power capacity development in the North Sea and the Baltic Sea. A ‘base case’ system of radial connection to the onshore transmission nodes was compared with an interlinked (meshed) HVDC offshore grid linking the countries around the North Sea and the Baltic Sea. A preliminary analysis indicates not only a better cost-benefit ratio for the meshed grid than for the radial connection solution, but also that the investments are justified from an economic point of view. It is recommended that the necessary onshore reinforcement is considered in a further analysis. This could not be done in the TradeWind project because of the limitations of the available network data. TradeWind proposes a meshed offshore transmission configuration concept linking direct extensions to major load centres inland. Because of the multiple technical and commercial benefits of such a network configuration, TradeWind recommends making more detailed studies based on this concept.

Capacity credit and contribution of European aggregated wind power to generation adequacy

Tradewind used the European wind power time series to calculate the effect of geographical aggregation on the contribution of wind power to generation adequacy.

In almost all cases it was found that wind power generation is higher than average during peak load hours. The countries studied by TradeWind show an average wind power capacity factor of 30-40% during the 100 highest peak load situations for the 2020 Medium scenarios. This value is strongly determined by the wind power capacities in UCTE2 (Germany, France).

Alongside this correlation of power demand and wind power output, and its positive effect on the capacity credit, a probabilistic capacity credit calculation looked into the effect aggregating wind power from larger areas has on the capacity credit. The results for the 2020 Medium scenario show that aggregating wind energy production from multiple countries strongly increases the capacity credit and the greater geographic area the grouped countries represent, the higher the capacity credit is. If no wind energy is exchanged between the European countries, the capacity credit in Europe is 8%, which corresponds to 16 GW. When Europe is calculated as one wind energy production system and wind energy is distributed across multiple countries according to individual load profiles, the capacity credit almost doubles to 14%, which corresponds approximately to 27 GW of firm power in the system.

In order to maximise the contribution of wind power to system adequacy, there needs to be sufficient power exchange capacity between the Member States. This would be beneficial when, for example, there is high wind energy production and a surplus of power in one country, whereas in a neighbouring country there is a high load demand situation and a need for imported power. TradeWind has made a preliminary analysis of the opportunities and possible increments of the capacity credit at EU level. Reinforcement of cross border transmission capacity will be beneficial for the capacity credit and system security.

Looking at the above figures it becomes clear that wind capacity has a non-negligible potential to replace conventional capacity with a high degree of reliability. Hence, there is a need to establish a harmonised method for calculating the capacity credit of wind power to be used in system adequacy forecasts at EU level.

Wind power in the European power market

TradeWind assessed whether power markets are suitable for the integration of wind power by determining the market’s efficiency for different market designs and stages of market integration. Based on the present situation and recent steps towards liberalisation and integration in the European power market, existing inefficiencies were quantified by analysing of empirical market data. The sensitivity of the market to market design criteria was assessed by simulations made with the market analysis tools WILMAR and PROSYM.

Regarding the specific properties of wind power generation, the TradeWind analysis took the main parameters influencing the market integration of wind power to be flexibility of rescheduling (time dimension) and the flexibility of the cross-border exchange (spatial dimension), where the available interconnector capacity should be considered as a boundary condition or constraint.

In an energy economic context defined by the electricity demand, the generation mix including the overall wind power share and the prices of fossil fuel and CO_2 emission allowances, TradeWind identified a selected number of cases - representing different stages of flexibility and market integration - to be simulated with the WILMAR and PROSYM tool.

From the simulations of these cases it was found that the costs of power generation from 2020 to 2030 with a large share of wind power will exhibit a strong sensitivity to fuel prices and a significant sensitivity to the amount of energy generated from wind. For example, doubled fuel prices as compared to the European Commission's latest baseline scenario for 2020 will lead to a 23% increase in power generation costs. Conversely, thanks to the new wind farms to be installed between 2008 and 2020, the costs of power generation are reduced by 10%, which can be interpreted as a return on the public investment via support schemes.

Requirements for a good market design in Europe are:

- Features for intra-day rescheduling of generators and trade on an international level for low system costs and stable prices
- Wide-spread application of implicit auctioning to allocate cross-border capacity (i.e. market coupling, market splitting etc.)
- Application of intra-day wind power forecasting for low reserve requirements
- Interconnection capacity sufficient to enable prices to converge


Source: EWEA/Beurskens

Changing from day-ahead into intra-day rescheduling will reduce system costs by 0.2% to 1%, assuming a perfect market. In reality, cost reductions will be more significant. Installation of 128 GW of wind power between 2008 and 2020 yields a 10% reduction in annual system costs in 2020 as compared to a situation with no additional wind power capacity after 2008. The savings would be proportionally higher with higher prices for fossil fuel.

Wind power curtailment and load shedding are almost insignificant when there is a good market design as specified. An international exchange of reserves is not the first priority for a good market design.

Final remarks

TradeWind's expertise, approach, data and models have given this first analysis of the European transmission and market system in view of the integration of large amounts of wind power. Due to the time restrictions, it was not possible to make optimal use and analysis of all the produced simulation outputs. Therefore it is recommended that similar studies are made, based on the data sets produced by TradeWind.

For the future, alternative means of obtaining Europe-wide consistent wind speed data sets of several years' duration and time resolution should be considered. Such data should have shorter resolution times than the six hour intervals in the Reanalysis data used by TradeWind. Such data will be useful for studying generation adequacy, balancing costs, and so on. TradeWind believes that there is no justification for using resolution times of under an hour. Indeed, it is likely that two- or three-hour resolutions - linearly interpolated to hourly data – will be extremely similar to results from one-hour resolution times.

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Appendix

TABLE A-1: Wind power scenarios per country (MW)

		Actual 2005	Low 2008	Medium 2008	High 2008	Low 2010	Medium 2010	High 2010
AT	Austria	819	990	**1,015**	1,045	1,100	**1,160**	1,250
BE	Belgium	167	357	**571**	834	469	**750**	1,119
BU	Bulgaria	10	30	**40**	55	90	**183**	245
HR	Croatia	6	150	**230**	360	250	**400**	600
CZ	Czech Republic	29	120	**220**	350	180	**580**	1,100
DK	Denmark	3,130	3,129	**3,129**	3,286	3,329	**3,629**	4,229
FI	Finland	82	150	**200**	250	250	**350**	500
FR	France	702	2,100	**2,700**	5,100	3,098	**4,840**	9,680
DE	Germany	18,428	21,622	**22,900**	24,063	22,665	**25,291**	28,466
GB	Great Britain	1,460	2,822	**4,086**	6400	5,550	**7,512**	8,900
GR	Greece	573	845	**1,098**	1,350	958	**1,479**	2,000
HU	Hungary	17	105	**250**	325	250	**325**	330
IE	Ireland	583	1,246	**1,326**	1,525	1,478	**1,955**	2,858
IT	Italy	1,381	2,075	**4,233**	5,810	2,490	**5,893**	8,300
LU	Luxembourg	35	45	**54**	53	54	**66**	66
NL	Netherlands	1,224	2,058	**2,228**	2,328	2,528	**2,950**	3,400
NO	Norway	274	454	**544**	595	508	**1,057**	1,458
PL	Poland	83	450	**550**	650	1,000	**1,200**	1,500
PT	Portugal	1,014	2,699	**2,841**	2,983	3,894	**4,099**	4,304
RO	Romania	1	50	**80**	120	160	**345**	460
SC	Serbia	0	0	**2**	5	5	**10**	30
SK	Slovakia	5	20	**55**	90	100	**175**	410
SI	Slovenia	0	0	**20**	40	0	**85**	130
ES	Spain	11,482	13,929	**15,477**	17,025	17,528	**19,475**	21,423
SE	Sweden	493	750	**1,050**	1350	1,100	**1,600**	2,150
CH	Switzerland	12	15	**18**	20	15	**40**	100
	Total	**42,011**	**56,212**	**64,917**	**76,012**	**69,047**	**85,449**	**105,007**

		Low 2015	Medium 2015	High 2015	Low 2020	Medium 2020	High 2020	Low 2030	Medium 2030	High 2030
AT	Austria	1,400	**3,000**	3,400	1,700	**3,500**	4,900	2,300	**4,300**	7,900
BE	Belgium	986	**1,286**	1,952	1,218	**2,289**	3,034	2,262	**4,983**	6,086
BU	Bulgaria	300	**540**	650	680	**875**	1,150	1,495	**2,160**	3,450
HR	Croatia	370	**580**	1,150	700	**1,400**	2,800	1,200	**3,000**	5,600
CZ	Czech Republic	220	**900**	1,800	230	**1,200**	2,500	250	**1,500**	4,000
DK	Denmark	3886	**4,318**	4,750	4,778	**5,309**	5,840	6,562	**7,291**	8,020
FI	Finland	500	**900**	1,600	1,000	**1,700**	3,000	2,000	**3,200**	6,000
FR	France	12,313	**16,745**	23,000	23,000	**30,000**	37,000	38,000	**45,000**	49,950
DE	Germany	27,383	**36,004**	42,612	34,170	**48,202**	56,640	44,857	**54,244**	63,587
GB	Great Britain	6,864	**10,813**	16,979	9,995	**16,278**	26,087	11,059	**18,136**	29,183
GR	Greece	1,988	**2,744**	3,500	2,280	**3,640**	5,000	3,126	**5,628**	8,130
HU	Hungary	330	**450**	500	330	**850**	900	330	**900**	1,600
IE	Ireland	1,747	**3,257**	4,444	2,993	**4,537**	5,344	3,295	**4,998**	5,891
IT	Italy	3,403	**9,130**	12,865	4,150	**11,620**	15,770	6,640	**15,355**	19,090
LU	Luxembourg	78	**96**	98	102	**126**	132	117	**184**	206
NL	Netherlands	4,100	**5,250**	6,700	5,100	**6,950**	10,100	5,150	**7,050**	10,200
NO	Norway	940	**2,350**	4,070	1,380	**3,660**	6,660	1,990	**5,980**	11,970
PL	Poland	3,000	**3,500**	4,000	5,000	**6,000**	7,000	10,000	**12,000**	14,000
PT	Portugal	5,365	**5,647**	5,930	6,850	**7,211**	7,572	8,516	**8,964**	9,412
RO	Romania	600	**1,100**	1,350	1,600	**2,500**	3,100	2,300	**3,300**	4,000
SC	Serbia	20	**40**	80	40	**80**	150	100	**200**	500
SK	Slovakia	160	**245**	545	177	**280**	545	205	**303**	545
SI	Slovenia	102	**220**	340	205	**430**	560	310	**540**	860
ES	Spain	23,028	**26,476**	30,924	29,029	**34,477**	39,425	40,031	**48,479**	53,427
SE	Sweden	2,150	**3,600**	5,600	4,000	**6,500**	10,000	6,500	**10,000**	17,000
CH	Switzerland	50	**150**	300	100	**300**	600	300	**600**	1,100
	Total	**101,282**	**139,342**	**179,139**	**140,807**	**199,915**	**255,808**	**198,895**	**268,295**	**341,707**

TABLE A-2: Annual electricity consumption for power flow and market modelling in TWh; scenario based on Eurprog 2006 [8]

COUNTRIES	2005	2008	2010	2015	2020	2030
DE	556	566	572	573	575	572
NL	115	122	129	143	157	191
BE	88	93	97	103	109	109
LU	6	7	6	7	7	7
FR	482	493	508	530	552	618
CH	63	64	65	72	80	98
IT	330	352	366	408	450	550
AT	63	65	63	66	70	83
ES	253	288	317	353	390	463
NO	122	128	133	138	143	153
SE	145	148	150	152	154	156
CZ	63	66	68	73	77	83
SI	13	15	16	17	18	20
GR	53	60	67	75	84	101
HU	39	43	45	49	53	58
GB	377	417	458	485	512	523
PT	50	55	59	67	76	97
HR	17	18	19	21	23	28
RS	42	45	48	53	58	58
RO	52	56	59	69	78	105
BG	36	36	36	44	51	62
BA	11	12	12	14	15	18
SK	26	29	31	33	35	39
PL	131	136	136	148	160	181
FI	85	93	96	101	107	117
DK	36	37	38	40	41	45
MK	8	8	8	8	8	8
IE	26	30	34	38	43	43
TOTAL	**3,288**	**3,482**	**3,636**	**3,880**	**4,126**	**4,586**

TABLE A-3: **Stage 1 branch reinforcements including planned new connections. Internal zones reinforcements are marked with grey colour.**[n]

YEAR	COUNTRIES		TYPE	RATE [MW]	COMMENTS
2008	BE	FR-2	AC	400	Planned: Chooz – Jamiolle - Monceau
	GR	MK		1,420	Planned: Bitola – Florina
	CZ	AT-1		1,386	Planned: 2d line Slavetice - Durnrhor
2009	NO	NL	HVDC	700	Planned: NorNed
2010	ES-2	FR-6	AC	3,100	Planned: France - Spain: eastern reinforcement
	DK	DE-2		1,660	Planned: Upgrading of Jutland - Germany
	DK	DK-E	HVDC	600	Planned: Great Belt
	GB	IE		500	Planned: East-West interc.
2011	NO-2	SE-3	AC	800	Planned: Nea – Järpstrømmen
	NL	GB	HVDC	1,000	Planned: BritNed
2015	IT-2	SI	AC	3,100	Planned: Udine – Okroglo
	PT	ES-1		1,500	Planned: Valdigem - Douro Internacional - Aldeadavilla
	PT	ES-4		3,100	Planned: Algarve - Andaluzia
	PT	ES-1		3,100	Planned: Galiza – Minho
	RO	RS		1,420	Planned: Timisoara – Varsac
	SE	FI	HVDC	800	Planned: Fenno scan 2
2020	IT-2	AT-2	AC	3,100	Planned: Thaur – Bressanone (Brenner Basis Tunnel)
	AT-1	HU		1,514	Planned: Wien/Südost - Gÿor
	AT-2	IT-2		530	Planned: Nauders – Curon / Glorenza
	AT-2	IT-2		3,100	Planned: Lienz – Cordignano
	DE-1	DE-1		751	North-East upgrade done in connection with Polish grid, see [TEN-E]
	DE-1	PL-1		392	
	DE-2	DE-2		2,764	Internal North-West Germany
	DE-5	DE-5		5,094	Internal Midwest Germany
	NO	DK	HVDC	600	Planned: Skagerrak 4
	NO	DE		1,400	Planned: NorGer
2030	NL	BE	AC	2,746	Branch between the Netherlands and Belgium
	DE-1	DE-1		408	North-East upgrade done in connection with Polish grid, see [TEN-E]
	DE-3	DE-3		1,659	Internal Mid-Germany
	DE-4	DE-4		2,091	Internal South-East Germany
	DE-5	DE-5		1,698	Internal Midwest Germany
	ES-2	FR-6		330	Branch between Spain and France
	FR-3	CH-2		320	Branch between France and Switzerland
	NL	NO-1	HVDC	700	HVDC between the Netherlands and Norway
	GB	IE		1,000	HVDC between Great Britain and Ireland
	GB	FR-X		2,000	HVDC between Great Britain and France

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[n] The number after the country code (for example AT-2) indicates the grid zone within the country. Details can be found in the TradeWind WP6 report.

TABLE A-4: **Stage 2 branch reinforcements. Internal zones reinforcements are marked with grey colour.**[n]

YEAR	COUNTRIES		TYPE	RATE [MW]	COMMENTS
2015	ES-2	FR-6	AC	330	Upgrade between Spain and France
	FR-3	CH-2		320	Upgrade between France and Switzerland
	NL	NO-1	HVDC	700	Upgrade of NorNed between Norway and the Netherlands
	DK-E	DE-X		550	Upgrade between Denmark and Germany
	GB	FR-X		2,000	Upgrade between Great Britain and France
	NO-1	DK		350	Upgrade between Norway and Denmark
	DK	SE-2		360	Upgrade between Denmark and Sweden
	DE-X	SE-1		600	Upgrade between Germany and Sweden
	IT-X	GR-X		500	Upgrade between Italy and Greece
	PL-X	SE-1		600	Upgrade between Poland and Sweden
2020	NL	BE	AC	1,476	Upgrade between The Netherlands and Belgium
	NO-1	NO-1		1,000	Internal upgrade in South Norway
	DE-1	DE-1		1,659	Internal upgrade in North-East Germany
	DE-2	DE-2		1,695	Internal upgrade in North-West Germany
	DE-4	DE-4		301	Internal upgrade in South-East Germany
	DE-6	CH-1		1,131	Upgrade between Germany and Switzerland
	FR-1	FR-1		1,000	Internal upgrade in northern parts of France
	FR-4	IT-1		956	Upgrade between France and Italy
	IT-1	CH-2		1,510	Upgrade between Italy and Switzerland
	DK-E	DK	HVDC	600	Internal upgrade between Denmark East and West
	NO-1	NO-2		1,000	Internal upgrade between South and Mid-Norway.
	IT-X	GR-X		500	Upgrade between Italy and Greece
2030	NO-1	NO-1	AC	1,000	Internal upgrade in South Norway
	AT-1	DE-4		602	Upgrade between Austria and Germany
	DE-1	DE-1		1,659	Internal upgrade in North-East Germany
	DE-2	DE-2		3,077	Internal upgrade in North-West Germany
	DE-2	DE-3		1,369	Internal upgrade between North-West and Mid-Germany
	DE-6	CH-1		1,158	Upgrade between Germany and Switzerland
	FR-3	CH-2		640	Upgrade between France and Switzerland
	IT-1	CH-2		514	Upgrade between Italy and Switzerland
	GB	NO-1	HVDC	2,000	New HVDC between Great Britain and Norway
	HR	IT-2		1,000	New HVDC between Croatia and Italy
	FR-4	IT-1		1,000	New HVDC between France and Italy

TABLE A-5: **Stage 3 branch reinforcements. Internal zones reinforcements are marked with grey colour.**[n]

YEAR	COUNTRIES		TYPE	RATE [MW]	COMMENTS
2030	NL	BE	AC	1,476	Upgrade between The Netherlands and Belgium
	NO-1	NO-1		1,210	Internal upgrade in Southern Norway
	DE-2	DE-2		2,764	Internal upgrade in North-West Germany
	DE-5	DE-5		1,698	Internal Midwest Germany
	FR-3	CH-1		1,046	Upgrade between France and Switzerland
	IT-1	CH2		514	Upgrade between Italy and Switzerland
	IT-X	GR-X	HVDC	500	Upgrade between Italy and Greece
	FR-4	IT-1		1,000	Upgrade between France and Italy
	NO-1	DE-2		1,000	Upgrade between Norway and Germany

FIGURE A-1: **Comparison of simulated year 2005 electricity transfers between countries are compared to these actual transfer values given by TSOs** [v,w,x].

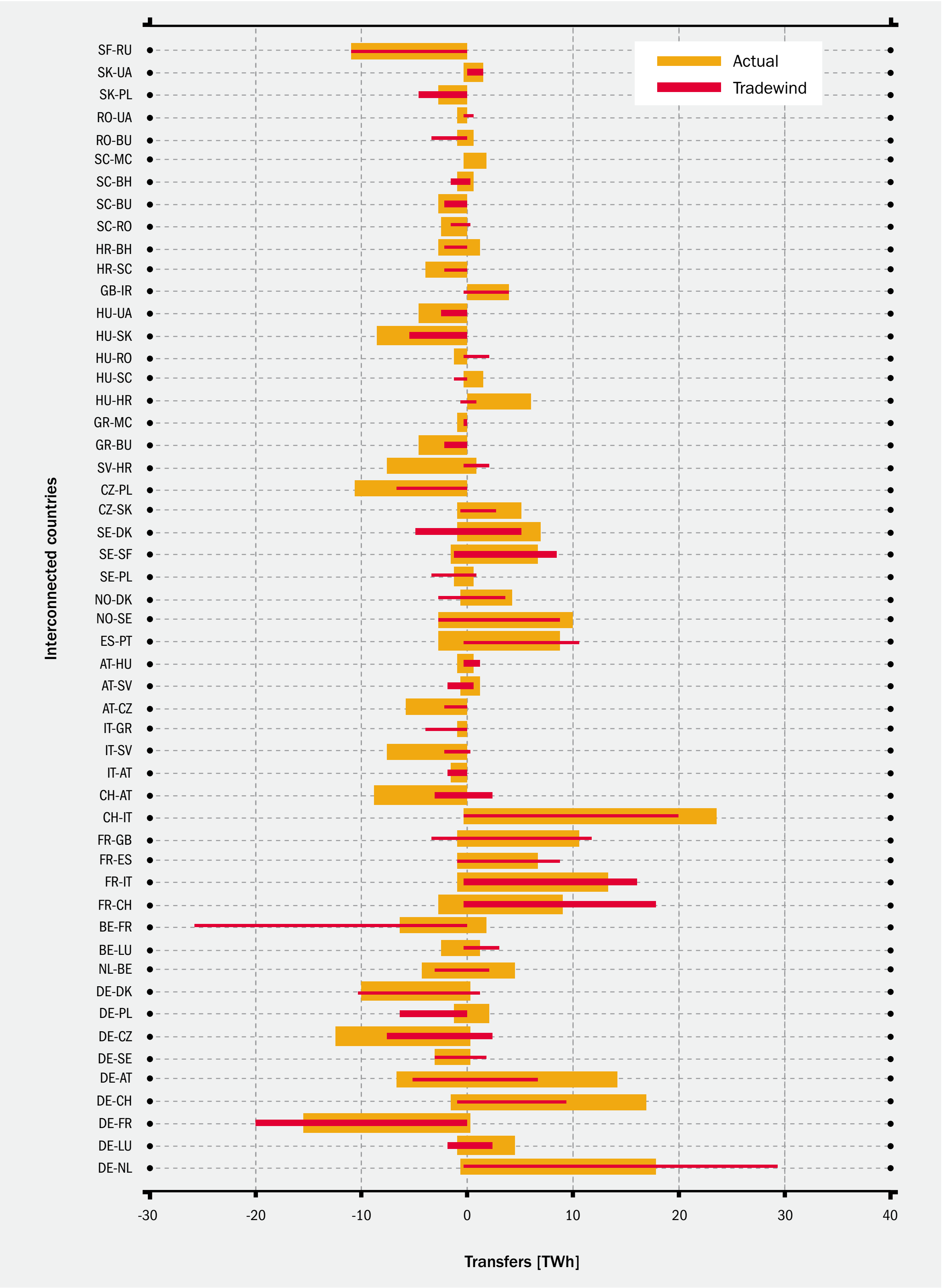


FIGURE A-2: **Electricity transfers at cross-borders for the different scenario years**

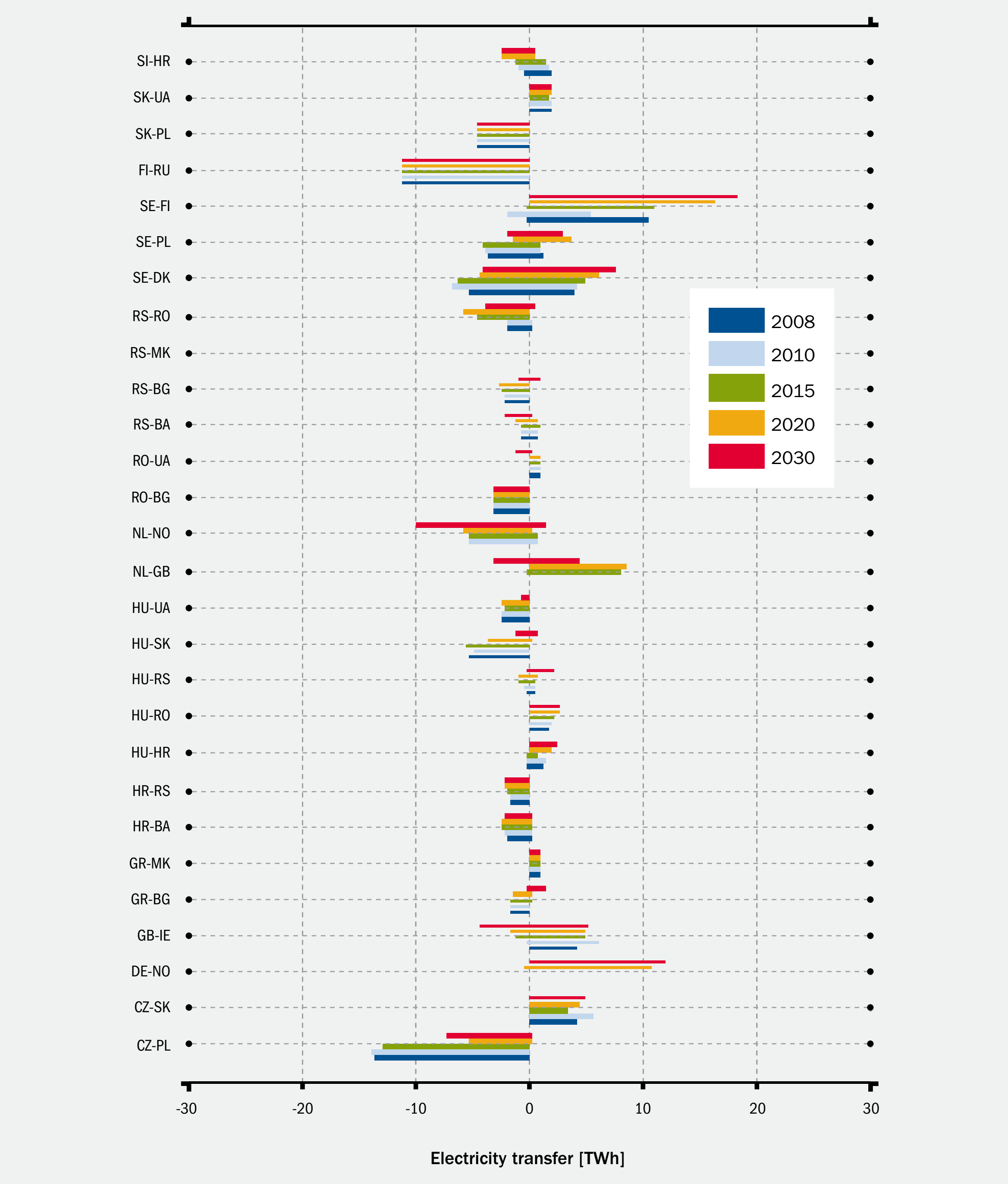
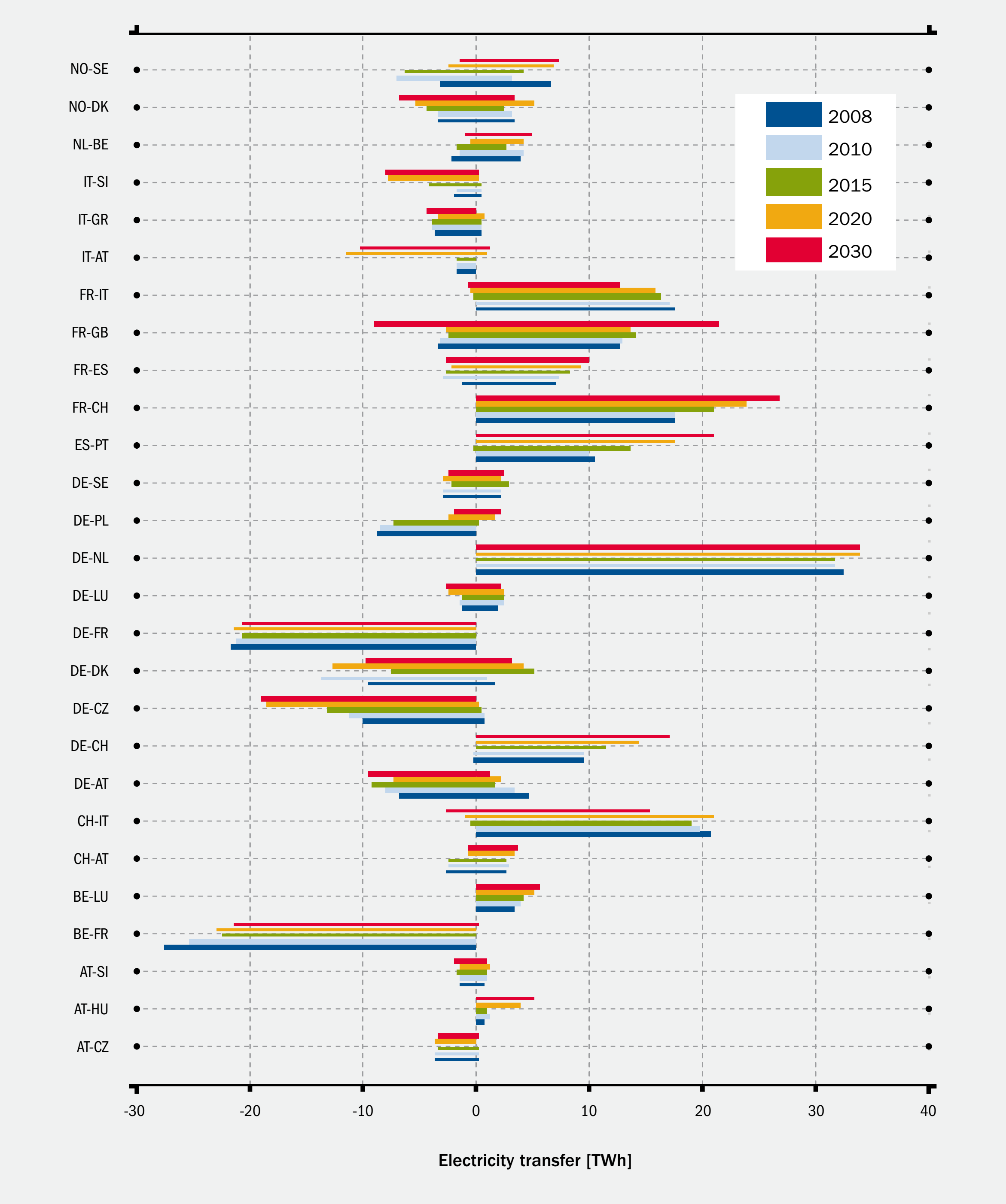


FIGURE A-2 (continued): **Electricity transfers at cross-borders for the different scenario years**



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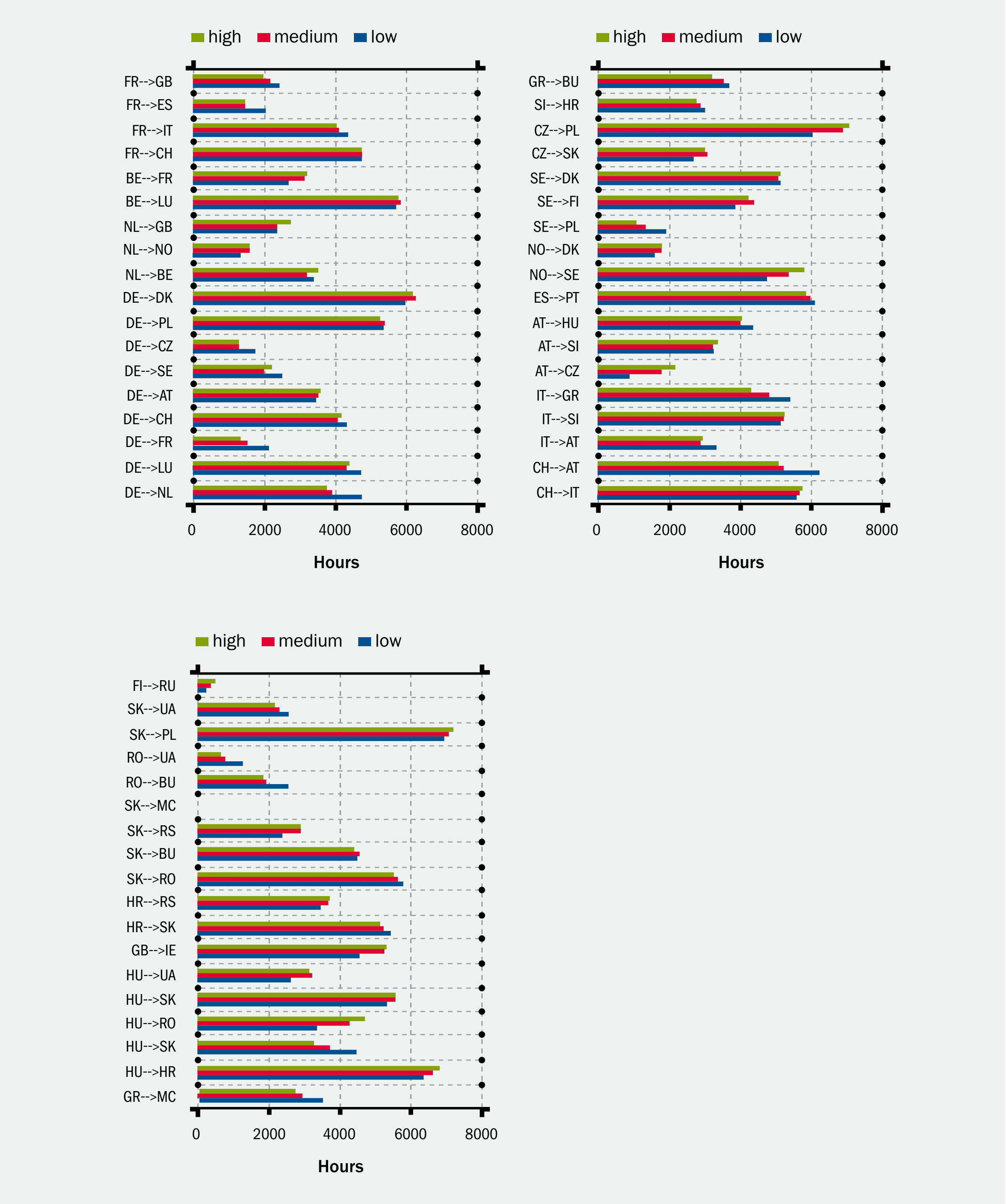
[v] www.ucte.org/services/onlinedatabase/exchange Visited on 4.6.2008.

[w] Nordel Annual Statistics 2005.
Available at www.nordel.org/content/Default.asp?PageID=213 Visited on 4.6.2008.

[x] www.berr.gov.GB/files/file45407.pdf Visited on 6.6.2008.

FIGURE A-3: **Hours of deviation between planned and actual cross border flow 2015**



Country Codes

AT	Austria
BE	Belgium
BG	Bulgaria
CH	Switzerland
CZ	Czech Republic
DE	Germany
DK	Denmark
DK-E	Denmark East
DK-W	Denmark West
ES	Spain
FI	Finland
FR	France
GB	Great Britain
GR	Greece
HR	Croatia
HU	Hungary
IE	Ireland
IT	Italy
LU	Luxembourg
MK	Former Yugoslav Republic of Macedonia
NI	Northern Ireland
NL	Netherlands
NO	Norway
PL	Poland
PT	Portugal
RO	Romania
RS	Serbia
RU	Russian Federation
SE	Sweden
SI	Slovenia
SK	Slovakia
UA	Ukraine
UK	United Kingdom

Glossary

Active Power	Is a real component of the apparent power, usually expressed in kilowatts (kW) or megawatts (MW), in contrast to REACTIVE POWER.
Adequacy	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 standard conditions.
Ancillary Services	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.
Availability	AVAILABILITY is a measure of time during which a generating unit, transmission line, ANCILLARY SERVICE or another facility is capable of providing a service, whether or not it actually is in service. Typically, this measure is expressed as a percentage available for the period under consideration.
Available Transfer Capacity (ATC)	AVAILABLE TRANSFER CAPACITY is a measure of the transfer capability remaining in the physical TRANSMISSION network for further commercial activity over and above already committed uses. AVAILABLE TRANSMISSION CAPACITY is the part of NTC that remains available after each phase of the allocation procedure for further commercial activity. ATC is defined by the following equation: ATC = NTC- AAC.
Capacity	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.
Capacity Factor	CAPACITY FACTOR (load factor) is the ratio between the average generated power in a given period and the installed (rated) power.
Consumption	see: DEMAND
Contingency	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.
Control Area (CA)	A CONTROL AREA is a 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.
Control Block (CB)	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.
Curtailment	CURTAILMENT means a reduction in the scheduled capacity or energy delivery.
Demand {Consumption}	DEMAND is the rate at which electric power is delivered to or by a system or part of a system, generally expressed in kilowatts (kW) or megawatts (MW), at a given instant or averaged over any designated interval of time. DEMAND should not be confused with LOAD (a LOAD is usually a device).
Disturbance	DISTURBANCE is an unplanned event that produces an abnormal system condition.
Electrical Energy	ELECTRICAL ENERGY is a measure of the generation or use of electric power by a device integrated over a period of time; it is expressed in kilowatt-hours (kWh), megawatt-hours (MWh), or gigawatt-hours (GWh).
Electric System Losses	ELECTRIC SYSTEM LOSSES are total electric energy losses in the electric system. The losses consist of TRANSMISSION, transformation, and distribution losses between supply sources and delivery points. Electric energy is lost primarily due to heating of transmission and distribution elements.
Exchange Programme (CAX, CBX)	An EXCHANGE PROGRAMME represents the total scheduled energy interchange between two CONTROL AREAS (CAX) OR BETWEEN CONTROL BLOCKS (CBX).
Exchange Schedule (CAS, CBS)	An EXCHANGE SCHEDULE defines an agreed transaction with regard to its size (megawatts), start and end time, RAMP PERIOD and type (e.g. firmness); it is required for delivery and receipt of power and energy between the contracting parties and the CONTROL AREA(S) (CAS) or between control areas and control blocks (CBS) involved in the transaction.
Frequency	See: SYSTEM FREQUENCY
Gate Closure	The point in time when generation and demand schedules are notified to the system operator.
Generation	GENERATION is the rate at which a GENERATION SET delivers electric power to a system or part of a system, generally expressed in kilowatts (kW) or megawatts (MW), at a given instant or averaged over any designated interval of time, see also: DEMAND.
Interconnected System	An INTERCONNECTED SYSTEM is a system consisting of two or more individual electric systems that normally operate in synchronism and are physically connected via TIE-LINES, see also: SYNCHRONOUS AREA.
Interconnection	An INTERCONNECTION is a transmission link (e.g. TIE-LINE or transformer) which connects two CONTROL AREAS.
Load	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.
Load-Shedding	LOAD-SHEDDING is the disconnection of LOAD from the synchronous electric system, usually performed automatically, to control the SYSTEM FREQUENCY in emergency situations.
Loop Flows	See: PARALLEL PATH FLOWS.

Minute Reserve {15 Minute Reserve}	See: TERTIARY CONTROL RESERVE
N-1 Criterion	The N-1 CRITERION is a rule according to which elements remaining in operation after failure of a single network element (such as transmission line / transformer or generating unit, or in certain instances a busbar) must be capable of accommodating the change of flows in the network caused by that single failure.
(N-1)-Safety	(N-1) SAFETY means that any single element in the power system may fail without causing a succession of other failures leading to a total system collapse. Together with avoiding constant overloading of grid elements, (N-1)-safety is a main concern for the grid operator.
Net Transfer Capacity (NTC)	The NET TRANSFER CAPACITY is defined as: NTC = TTC-TRM 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.
Operating Procedures	OPERATING PROCEDURES are a set of policies, practices, or system adjustments that may be automatically or manually implemented by the system operator within a specified time frame to maintain the operational integrity of the INTERCONNECTED SYSTEMS.
Parallel Path Flows {loop flows, circulating power flows, unscheduled power flows}	PARALLEL PATH FLOWS describe the difference between the scheduled and actual power flow, assuming zero inadvertent interchange, on a given transmission path in a meshed grid.
Power Curve	The POWER CURVE is the relationship between net electric output of a wind turbine and the wind speed measured at hub height on 10 min average basis.
Power System	The POWER SYSTEM comprises all generation, consumption and network installations interconnected through the network.
PX	The PX is a Power Exchange Scheduling Coordinator, and is independent of System Operators and all other market participants.
Reactive Power	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.
Reliability (To a great extent, the overall RELIABILITY of the electric power supply (for customers being connected to the distribution grid), that is usually measured, is defined by the RELIABILITY of the power distribution instead of the transmission or generation.)	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.

Security Limits {Operating Security Limits}	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.
Stability	is the ability of an electric system to maintain a state of equilibrium during normal and abnormal system conditions or disturbances.
Static Load Flow Calculations	SLFC investigate the risk of system overload, voltage instability and (N-1)-safety problems. System overload occurs when the transmitted power through certain lines or transformers is above the capacity of these lines/transformers. System static voltage instability may be caused by a high reactive power demand of wind turbines. Generally speaking, a high reactive power demand causes the system voltage to drop.
Synchronous Area	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.
System Frequency {Frequency}	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).
Tie-Line	A TIE-LINE is a circuit (e.g. a transmission line) connecting two or more CONTROL AREAS or systems of an electric system.
Total Transfer Capacity (TTC)	TOTAL TRANSFER CAPACITY is the maximum EXCHANGE PROGRAMME between two ADJACENT CONTROL AREAS that is compatible with operational security standards applied in each system (e.g. Grid Codes) if future network conditions, generation and load patterns are perfectly known in advance.
Transmission	TRANSMISSION is the transport of electricity on the extra-high or high-voltage network (transmission system) for delivery to final customers or distributors. Operation of TRANSMISSION also includes the tasks of system operation concerning the management of energy flows, reliability of the system and availability of all necessary system services / ANCILLARY SERVICES.
Transmission System Operator (TSO)	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 Synchronous Area	A UCTE synchronous area is a part of a SYNCHRONOUS AREA covered by INTERCONNECTED SYSTEMS / TSOs which are members of the association. Different UCTE SYNCHRONOUS AREAS may exist in parallel on a temporary or permanent basis.

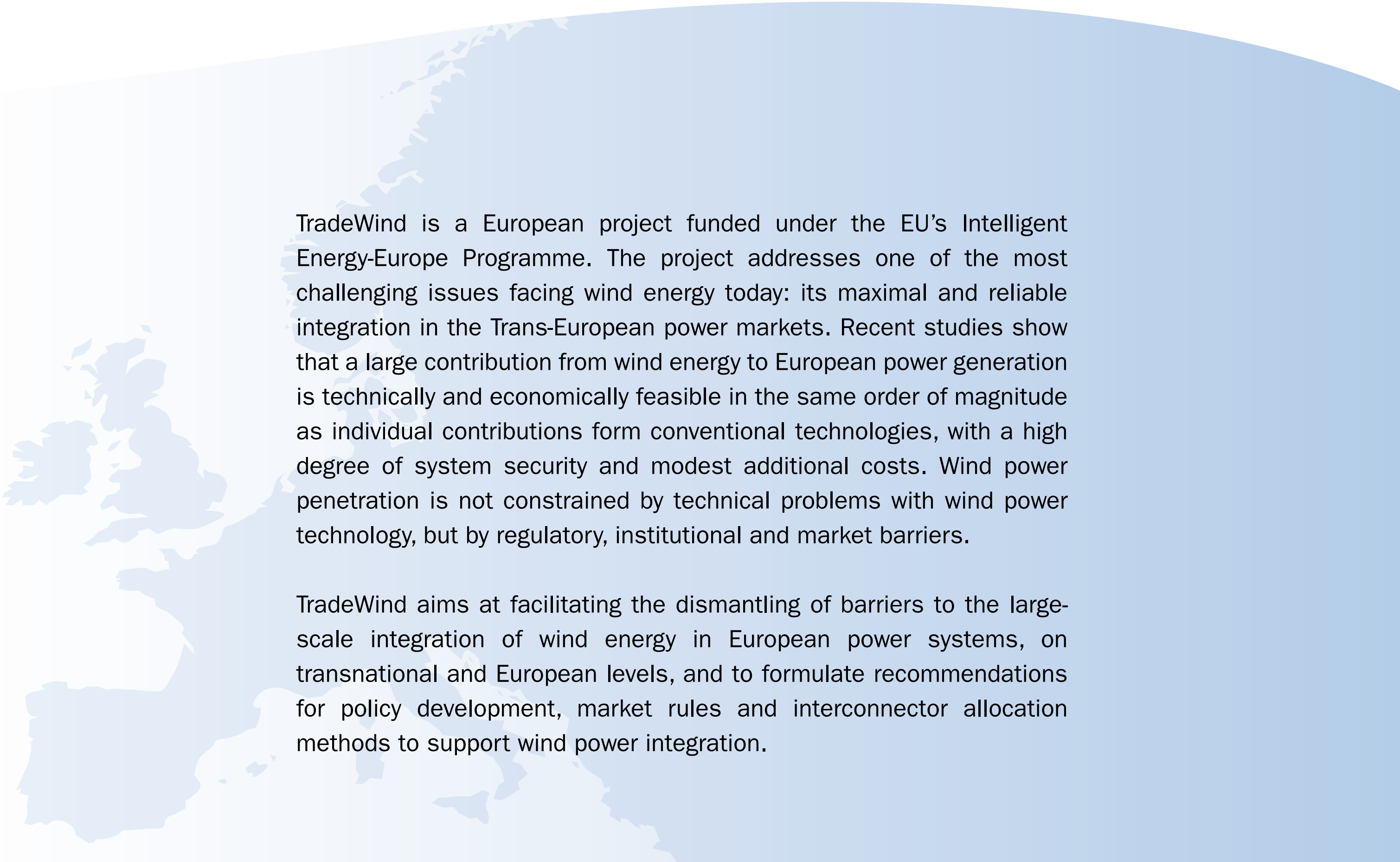
Symbols and abbreviations

AC	Alternating Current
AllDay market	Day-ahead scheduling of unit commitment of slow units and power exchange
AllInt market	Intra-day rescheduling of both unit commitment and power exchange
AllIntExRes market	Intra-day rescheduling combined with possibility of exchanging reserve power across borders
ANEMOS	Development of a next generation wind resource forecasting system for the large-scale integration of onshore and offshore wind farms (Project ENK5-CT-2002-00665)
ATC	Available Transfer Capacity (sum of line capacities)
BELPEX	Belgian Power Exchange
CO_2	Carbon dioxide
CSP	Concentrating Solar Power
DB	Database
DC	Direct Current
DG TREN	Directorate-General Energy and Transport
EACI	Executive Agency for Competitiveness and Innovation
EEX	European Power Exchange
EFET	European Federation of Energy Traders
ENTSO-E	European Network for Transmission System Operators for Electricity
EPC	Equivalent Wind Power Curve
ERGEG	European Regulators' Group for Electricity and Gas
ETSO	European Transmission System Operators
EU	European Union
EURPROG	Statistics and prospects for the the European electricity sector
EWEA	European Wind Energy Association
EWIS	European Wind Integration Study
ExDay market	Intra-day rescheduling of unit commitment but still day-ahead scheduling of power exchange
FACTS	Flexible AC Transmission Systems
GHG	Greenhouse gas
GW	Gigawatt (1 billion watts)
HVDC	High-voltage - Direct current
Hws	High wind speed
IEA	International Energy Agency
IEE	Intelligent Energy - Europe
kV	Kilovolts
m/s	Metres per second
MIBEL	Iberian Electricity Market
MULTISYM	MULTISYM is a superset of PROSYM that is able to convert PROSYM into a multi-area model by taking transmission constraints into account.
MW	Megawatt (1 million watts)
MWh	Megawatt hours (power in megawatts multiplied by time in hours)
NTC	Net Transfer Capacity
PROSYM	Proprietary Hourly Power System Evaluation Model
psd	Power spectral density
PSST	Power System Simulation Tool
PST	Phase Shift Transformer
PTDF	Power Transfer Distribution Factor
p.u.	Per unit
SAF	System Adequacy Forecast
SM	Scheduling Model
SSSC	Static Synchronous Series Compensator
STT	Scenario Tree Tool
SYSTINT	Joint EURELECTRIC and UCTE working group dealing with system development
TCSC	Thyristor-Controlled Series Capacitor
TEN-E	Trans-European Energy Networks
TSO	Transmission System Operator
TWh	Terrawatt hours (power in terrawatts multiplied by time in hours)
UCTE	Union for the Co-ordination of Transmission of Electricity
VTT	Technical Research Centre of Finland
W/km	Watts per kilometre
WILMAR	Wind power integration in a liberalised electricity market (ENK5-CT-2002-00663)
WP	Work Package

List of TradeWind reports

WORK PACKAGE	REPORT N°	TITLE	LEADING AUTHOR
Work Package 2: Wind Power Scenarios	2.1	Scenarios of installed wind power capacity	Garrad Hassan
	2.2	Forecast error of aggregated wind power	Risø- DTU
	2.3	Characteristic wind speed time series	Garrad Hassan
	2.4	Equivalent wind power curves	Garrad Hassan
	2.5	Aggregation of Wind Power Capacity Data	Garrad Hassan
Work Package 3: Preparation of Modelling and Simulations	3.2	Grid modelling and power system data	Sintef
	3.2	Grid modelling and power system data – Appendix: model updates	Sintef
Work Package 4: Identification of Market Rules	4.1	Detailed investigation of electricity market rules	Risø- DTU
Work Package 5: Continental Power Flows	5.1	Effects of increasing wind power penetration on the power flows in European grids	VTT
Work Package 6: Grid Scenarios	6.1	Assessment of increasing capacity on selected transmission corridors	Sintef
Work Package 7: Analysis of Market Rules	7.1	List of significant interconnectors for wind power exchange between countries	3E
	7.2	Analysis of the market and regulatory situation with current rules	3E
	7.3	Sets of market rules and allocation mechanisms as input for power market simulations	3E
	7.4	Proposal for adaptation of market rules in order to remove power market barriers: input for simulations	3E
	7.5	EU power market arrangement for efficient wind power integration: simulations and analysis	3E
	7.6	Analysis of market rules: conclusions	3E

TradeWind



TradeWind is a European project funded under the EU's Intelligent Energy-Europe Programme. The project addresses one of the most challenging issues facing wind energy today: its maximal and reliable integration in the Trans-European power markets. Recent studies show that a large contribution from wind energy to European power generation is technically and economically feasible in the same order of magnitude as individual contributions form conventional technologies, with a high degree of system security and modest additional costs. Wind power penetration is not constrained by technical problems with wind power technology, but by regulatory, institutional and market barriers.

TradeWind aims at facilitating the dismantling of barriers to the large-scale integration of wind energy in European power systems, on transnational and European levels, and to formulate recommendations for policy development, market rules and interconnector allocation methods to support wind power integration.

PROJECT PARTNERS:

EWEA THE EUROPEAN WIND ENERGY ASSOCIATION · GARRAD HASSAN · 3E · VTT · Tractebel Engineering SUEZ · dena German Energy Agency · RISØ DTU · SINTEF · KEMA

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