

RESEARCH ARTICLE

Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration

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ABSTRACT

There are dozens of studies made and ongoing related to wind integration. However, the results are not easy to compare. IEA WIND R&D Task 25 on 'Design and Operation of Power Systems with Large Amounts of Wind Power' collects and shares information on wind generation impacts on power systems, with analyses and guidelines on methodologies. In the state-of-the-art report (October, 2007), and the final report of the 3 years period (July, 2009) the most relevant wind power grid integration studies have been analysed especially regarding methodologies and input data. Several issues that impact on the amount of wind power that can be integrated have been identified. Large balancing areas and aggregation benefits of wide areas help in reducing the variability and forecast errors of wind power as well as help in pooling more cost effective balancing resources. System operation and functioning electricity markets at less than day-ahead time scales help reduce forecast errors of wind power. Transmission is the key to aggregation benefits, electricity markets and larger balancing areas. Best practices in wind integration studies are described. There is also benefit when adding wind power to power systems: it reduces the total operating costs and emissions as wind replaces fossil fuels and this should be highlighted more in future studies. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS

wind integration; grid integration; balancing; wind power forecast

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1. INTRODUCTION

Adding wind power will bring about a variable and only partly predictable source of power generation to a power system that has to balance generation and varying demand at all times.

1.1. Power system impacts of wind power

Wind power has impacts on power system operational security, reliability and efficiency. The studies address different impacts, and the different time scales involved usually mean different models (and data) used in impact studies. The case studies for the systemwide impacts have been divided to three focus areas: balancing, adequacy of power and grid (Figure 1). In this international collaboration (IEA WIND Task 25; <http://www.ieawind.org/AnnexXXV.html>), more system-related issues are addressed, as opposed to local issues of grid connection like power quality. Primary reserve is here denoted for reserves activated in seconds (systemwide frequency activated reserve; regulation; automatically activated reserve of the balancing zones). Secondary reserve is here denoted for reserves activated in 10...15 min (minute reserve; load following reserve; manually activated reserve).

High penetration of wind power has impacts that have to be managed through proper wind power plant interconnection, integration of the generation, transmission planning, and system and market operations. The final report of Task 25 first term presents a summary of selected, recently concluded studies of wind integration impacts from participating countries.¹ The case studies summarized are compared, although this is not an easy task due to different methodology and data used, as well as different assumptions on the interconnection capacity available.

There are already several power systems and control areas coping with large amounts of wind power.² The experience from Denmark, Spain, Portugal and Ireland that have integrated 13–20% of wind energy (percentage of annual gross demand as energy) show that wind power production will only have to be curtailed (regulated) at some rare instances, and that TSOs need on-line information of both the production and demand levels, as well as respective forecasts in their control rooms. Spain and Portugal have launched centres for distributed energy that convey data to TSOs and can even react to control needs. Suitable grid codes help to further increase the penetration level. All countries with experience on higher penetrations of wind, as well as several others, have implemented fault-ride-through requirements for wind power plants in order to keep a certain level of security of supply.

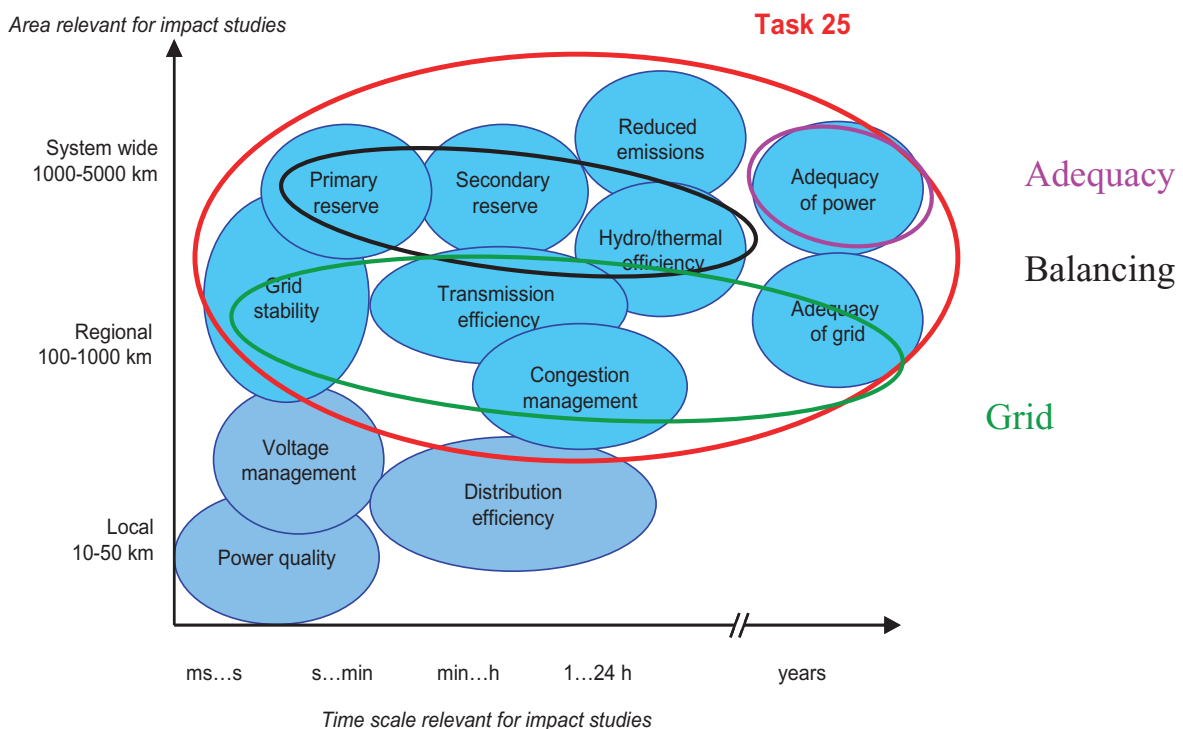


Figure 1. Impacts of wind power on power systems, displayed by time and spatial scales relevant for the studies.

1.2. Integration cost of wind power

Many studies assess the impacts of wind power, and some studies also estimate integration costs arising from the impacts. Integration cost is the extra investment and operational cost of the non-wind part of the power system when wind power is integrated.

Integration cost can be divided into different components arising from the increase in the operational balancing cost and grid reinforcement cost. It is important to note whether a market cost has been estimated or the results refer to technical costs for the power system. A 'market cost' includes transfer of money from one actor to another actor, while 'technical costs' implies a cost for the whole system.

Most studies so far have concentrated on the technical costs of integrating wind into the power system while cost-benefit analysis work is also emerging. The benefit when adding wind power to power systems is that it reduces the total operating costs and emissions as wind replaces fossil fuels. The integration costs of wind power need to be compared to something, like the production costs or market value of wind power, or the integration cost of other production forms. A fair comparison between power systems with differing amounts of wind power should, in principle, have systems with the same reliability, but also the same CO₂ emissions, or at least take the CO₂ emission costs into account. The value of the capacity credit of wind power can also be stated.

1.3. Defining wind penetration level

The penetration of wind power can be expressed by various measures. Often, either energy or capacity metrics are used: wind power production as a percentage of gross demand (energy) and wind power capacity as a percentage of peak load (capacity). These measures neglect, however, the presence of interconnecting capacity with neighbouring countries, though exactly the cross-border interconnections are many times the key to providing extra flexibility to power system operation. In particular, for the case of high wind and minimum load, operational constraints may be alleviated through utilizing cross-border transmission capacity for export of (excess) generation. It is thus relevant also to express wind penetration level in terms of wind capacity in percentage of the sum of minimum load and cross-border capacity. The power systems and highest wind penetrations presented in the case studies are summarized in Figure 2. It can be seen

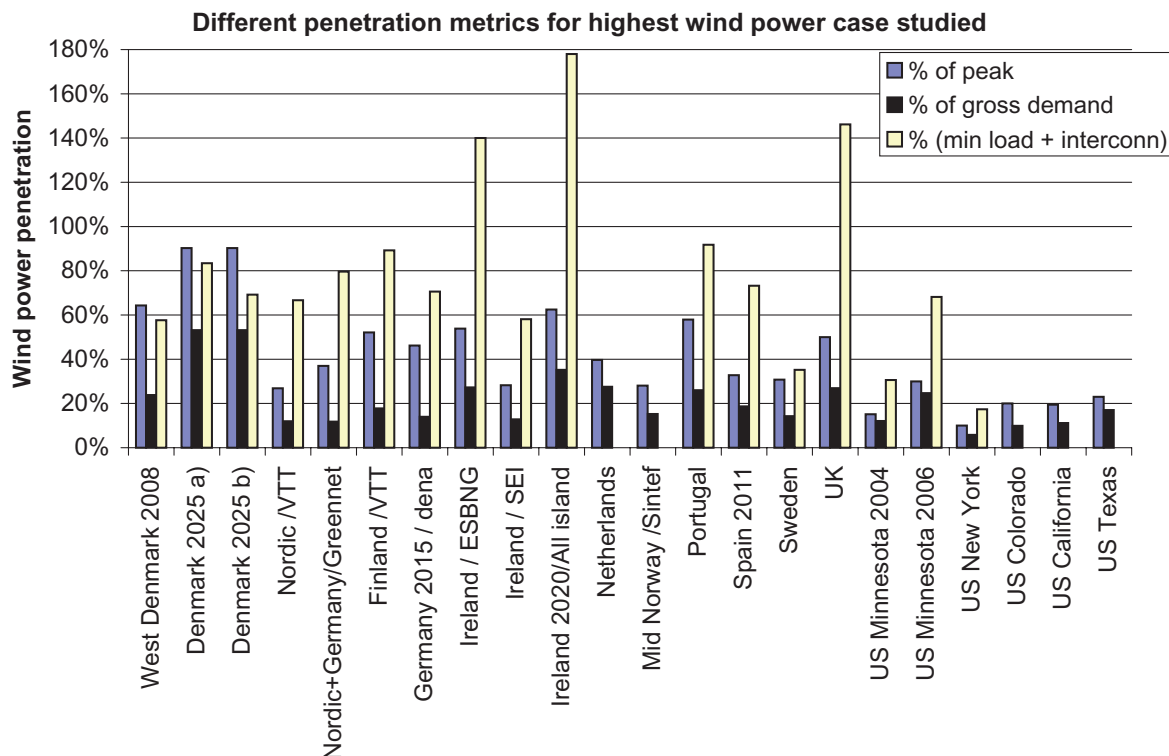


Figure 2. Comparison of the share of wind power in the power system (penetration levels) studied. For studies covering several countries, the aggregate penetration level has been calculated. Individual countries within the study cases can have significantly higher wind power penetration levels.

that taking into account the limitations of interconnection capacity, the penetration levels of Ireland and UK are more challenging than for the other European countries. For a small part of an interconnected system, a wind integration study stating a high penetration level can also be misleading if the wind penetration in neighbouring areas is low and interconnection capacity plays a major part in integration.

This paper summarizes the results of several wind integration studies carried out within the IEA Wind Task 25 research project. In Section 2, the short-term reserve requirements due to wind power are discussed, and Section 3 addresses the balancing costs related to wind power. In Section 4, other results to balancing are presented, and Section 5 looks at the costs of grid reinforcements due to wind power. The capacity value of wind power is discussed in Section 6, and recommendations for future wind integration studies are given in Section 7. Finally, Section 8 concludes and future work is discussed.

2. INCREASE IN SHORT-TERM RESERVE REQUIREMENTS DUE TO WIND POWER

Wind generation may require system operators to carry additional operating reserves. From both experience and results from studies performed, a significant challenge is the variability of wind power within 1–6 h. Inertial response, frequency control (time scale of seconds) and fast automatic balancing (time scales of seconds to minutes) are not crucial problems when integrating wind power into large systems at the present time, but can be a challenge for small systems or an isolated medium (like Ireland), and will become more of a challenge for systems with high penetration in the future.

2.1. Methodology

The increase in short-term reserve requirement is mostly estimated by statistical methods combining the variability or forecast errors of wind power with that of load and, in some cases, also power plant outages, and investigating the increase in the largest variations seen by the system.³ Usually, margins for ‘possible’ extreme situations are kept, i.e. a very small loss of load probability is allowed in a balancing area, which is to be balanced systemwide. The term ‘possible’ then normally includes a certain percentage of what in reality could happen. A straightforward method to define ‘possible’ is the commonly used ‘N-1 criterion’, i.e. it is necessary to keep reserves for an outage of the largest production unit or interconnector, which could be a challenge during both import and export situations. This is a common dimensioning criteria for disturbance (contingency) reserve. In addition, some operational reserve is carried on top of that to cover variability and forecast errors, but there are no commonly used criteria to dimension this part of reserve. Some TSOs are beginning to use probabilistic approaches to define a suitable level of reserves.

It is of central importance to separate the need for flexibility in longer time scales of several hours to a day (power plants that can follow net load variation) from the need for reserves that can be activated in the seconds or minutes time scale (power plants that can follow unforecasted net load variations). To illustrate the need for flexibility, Figure 3 shows the needed power increase divided into scheduled production and reserves.

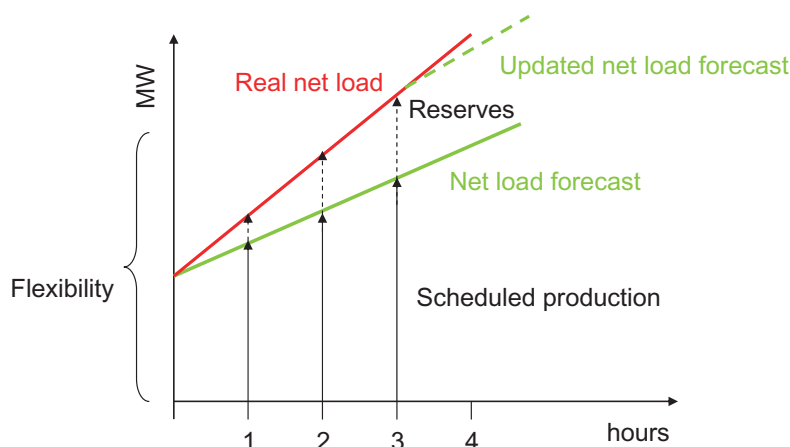


Figure 3. Flexibility in the power system to follow varying load and wind power production (the net load) consists of scheduled production and reserves.

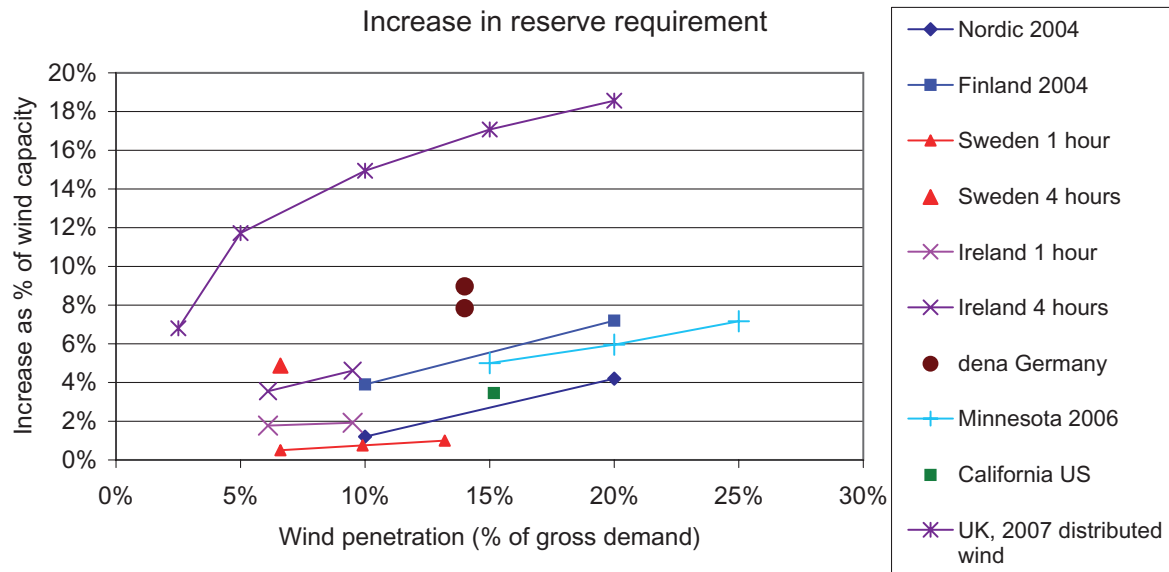


Figure 4. Results for the increase in reserve requirement due to wind power. German Dena estimates are taking into account the day-ahead uncertainty (for up and down reserves separately) and UK the variability of wind 4 h ahead. In Minnesota and California, day ahead uncertainty has been included in the estimate. For the others the effect of variations during the operating hour is considered. For Ireland and Sweden the 4 h-ahead uncertainty has been evaluated separately.

The need for flexibility is not the same as the need for reserves, since a part of the net load variation can be forecasted. Reserves mainly deal with forecast errors and the overall flexibility in scheduling deals also with the changes in output level for several hours and a day ahead.

2.2. Results from studies

The results presented in Figure 4 for increase in reserve requirements due to wind power are from the following studies: Finland and Nordic countries⁴; Sweden⁵; Ireland⁶; UK⁷; Germany⁸; Minnesota 2006⁹ and California¹⁰.

The estimated increase in short-term reserve requirements in the studies has a large range: 1–15% of installed wind power capacity at 10% penetration (of gross demand) and 4–18% of installed wind power capacity at 20% penetration. Time scales used in the estimation explain much of the differences in results:

- If only the hourly variability of wind is taken into account when estimating the increase in short-term reserve requirement, the results are 0.5–4% of installed wind capacity or less, with penetrations below 10% of gross demand.
- When 4 h forecast errors of wind power are taken into account, an increase in short-term reserve requirement of 4–5% of installed wind capacity has been reported, with penetration levels of 5–10% of gross demand.

The highest results in Figure 4 are from a study where 4 h variability of wind, assuming that no wind power forecast is used, is combined with load forecast error. This results in 15% reserve requirement at 10% penetration and 18% reserve requirement at 20% penetration of gross demand.⁷ The latest achievements in wind forecasting show a considerable improvement of predictions also in short time scales, so using updated forecasts would reduce this estimate. If day-ahead forecast errors are left to be balanced with the short-term reserves, the increase in short-term reserve requirement is nearly 10% (two points for Germany reflect the difference in up- and down-regulation requirements).⁸ In this German study, the reserve requirement is taken as the average impact of day-ahead forecast errors of wind power. The maximum values would result in an increase that is 15–20% of installed wind capacity.

In most studies, reserve requirements for different time frames are summed up—for example, increase in regulating reserves + increase in load following reserves. There are some studies showing a larger increase in reserve requirement than shown here. The Swedish TSO published estimates for reserves that are 35–48% of installed wind capacity. This is due to adding up several cases and time frames of reserves.¹¹ However, the different time frames, for example, 1 h ahead and 4 h ahead, are strongly overlapping. If one has enough flexibility for 4 h, then this in general implies that during this period there is enough flexibility for 1 h ahead. In this case, there is no meaning in summing up these reserve requirements

since they overlap significantly. Such additions are only valid when they contain reserve allocation in different generation units.

An important issue is that ‘increase in reserve requirements’ does not necessarily mean need of new investments; as a matter of fact, the experience so far from countries that have a lot of wind power shows that this is seldom the case. The amount of wind-caused reserves is at its highest when wind power is at a high production level. In these situations, the other power stations are usually operated at a low level, i.e. they can act as reserves and increase the generation if wind power decreases. This means that flexibility and reserve keeping in a system with wind power are mainly issues of ramp rates and start-up times and, sometimes, also a need of more capacity or a different kind of generation units. Faster ramping and starting capacity may be needed if the forecast errors are large enough that the slow units cannot follow. This must be considered when ‘increased reserve margins’ are to be estimated.

3. BALANCING COST

Wind power impacts on power system balancing can be seen in several time scales, from minutes to hours, up to the day-ahead time scale. General conclusions on the increase in balancing requirement will depend on the region size relevant for balancing, initial load variations and how distributed wind power is sited. Here, the operational routines of the power system are also relevant—how often the forecasts of load and wind are updated, for example.

3.1. Methodology

To arrive at estimates for balancing cost, the operating reserve impact is one issue (increase in reserve requirement from statistical methods) and impact on efficiency of conventional power plants for day-ahead operation is another issue (simulations). For the simulations, most results are based on comparing costs of system operation without wind and adding different amounts of wind. The costs of variability are also addressed by comparing simulations with flat wind energy to varying wind energy (for example in US Minnesota⁹ and Greenet Nordic + Germany).¹²

It is important to pay attention to the representativeness of wind input data (how well does the wind data represent the geospread of the power system, how is wind power simulated, what time scale effects on variability and predictability have been taken into account) and also how the main set-up for the assessment or simulation is made (wind power replacing other production or capacity and to what extent is the power system operation optimized when wind power production is added). It is important to have the wind data synchronous with load data to capture the correlations. The level of detail of the simulation model (time resolution, level of detail in simulating conventional generation and transmission, pricing) and how the uncertainty in the wind plant output forecast is handled with respect to the load forecast uncertainty are also important.

The matrix developed in Söder and Holttinen¹³ has been further processed to form a checklist for the national studies that have used simulations.¹ The checklist can be used to find out whether the approach has been conservative or whether some important aspects have been omitted, producing either high or low estimates for the impacts. The most general finding comparing the study set-ups is the use of interconnection capacity—this is crucial when estimating the impacts of wind power.

3.2. Results from studies

The results presented in Figure 5 for increase in balancing costs due to wind power are from the following studies: Finland and Nordic countries⁴; UK^{14,7}; Ireland⁶; Colorado¹⁵; Minnesota^{16,9}; California¹⁷; PacifiCorp¹⁸; Nordic countries and Germany.¹²

From the cost estimates presented in the investigated studies, it follows that at wind penetrations of up to 20% of gross demand (energy), system operating cost increases arising from wind variability and uncertainty amounted to about 1–4 €/MWh of wind power produced (Figure 5). This is 10% or less of the wholesale value of the wind energy. The actual impact of adding wind generation in different balancing areas can vary depending on local factors. Important factors identified to reduce integration costs are aggregating wind plant output over large geographical regions, larger balancing areas, and utilizing shorter gate closure times with accurate forecast systems and sub-hourly schedule changes.

The highest estimates of reserve requirements from Germany and the UK are not reflected in balancing costs, as from both studies, it was concluded that this amount of reserve can be handled with the current conventional power plants. From the UK, only the increased cost of operating existing reserves has been estimated.

In addition to estimates, there is some experience from Denmark for the actual balancing costs for the existing wind power. For West Denmark, the balancing cost from the Nordic day-ahead market has been 1.4–2.6 €/MWh for a 24% wind penetration (of gross demand). These numbers are quite in the middle of theoretically estimated results from studies

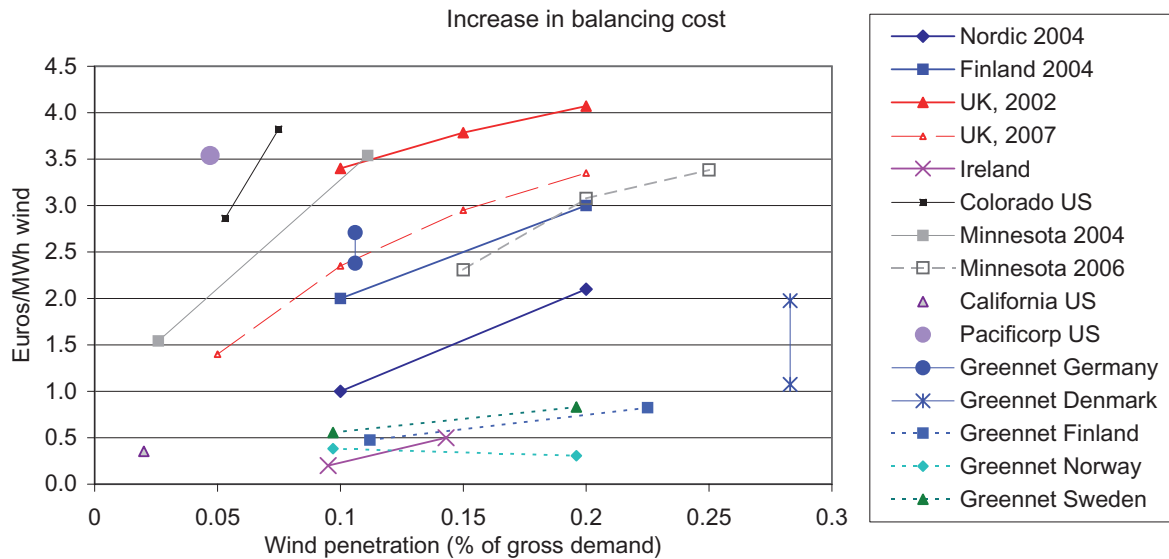


Figure 5. Results from estimates for the increase in balancing and operating costs due to wind power. The currency conversion used here is 1 € = 0.7 £ and 1 € = 1.3 US\$. For UK, 2007 study the average cost is presented here, the range in the last point for 20% penetration level is from 2.6 to 4.7 €/MWh.

depicted in Figure 3. The balancing cost paid by the wind power producers is not the same as the increase in the technical cost of balancing for that amount of wind power. However, the market costs from Denmark and Spain reflect the cost incurred to the system. In Denmark, the cost is low compared to the penetration level, as the cost comes from the Nordic market where wind power penetration is still small.

The interconnection capacity to neighbouring systems is often significant. For the balancing costs, it is then essential to note in the study setup whether the interconnection capacity can be used for balancing purposes or not. A general conclusion is that if interconnection capacity is also allowed to be used for balancing purposes, then the balancing costs are lower compared to the case where they are not allowed to be used. The two points for Greennet Germany at the same wind penetration level reflect that balancing costs increase when neighbouring countries get more wind (the same applies for Greennet Denmark). For a small part of an interconnected system, a wind integration study stating a high penetration level can also be misleading if the wind penetration in neighbouring areas is low and interconnection capacity plays a major part in integration.

4. OTHER BALANCING RELATED RESULTS

Not all case studies presented results quantified as MW of increase in reserve requirements or monetary values for increase in balancing costs.

In Denmark, the TSO has estimated the impacts of increasing the wind penetration level from 20% to 50% (of gross demand) and concluded that further large scale integration of wind power calls for exploiting both domestic flexibility and international power markets with measures on the market side, production side, transmission side and demand side.^{19,20}

For the Netherlands, the simulations show the benefit of international trade of electricity and postponing market gate closure for wind integration. Wind power worsens the business case for thermal generation, reducing CCGT during peak demand and base-load coal during low demand periods.²¹

The Irish All Island Grid Study shows that going from 2 to 6 GW wind, the operational costs of the electricity system fall by €13/MWh when compared to the base case. Due to cost benefit approach in the study, the wind integration cost component was not published as such, only the results of the total system costs that show the decrease of the total operating cost due to wind power replacing fuels for conventional generation.²²

For New York, with 10% penetration of capacity, incremental regulation due to wind was found to be 36 MW. No additional spinning reserve was needed. Incremental intra-hour load following burden increased 1–2 MW/5 min. Hourly ramp increased from 858 MW to 910 MW. All increased needs can be met by existing NY resources and market processes. System cost savings of \$335–\$455 million for assumed 2008 natural gas prices of \$6.50–\$6.80/MMBTU

were found. Day-ahead unit-commitment forecast error σ increased from 700–800 MW to 859–950 MW. Total system variable cost savings increases from \$335 million to \$430 million when state of the art forecasting is considered in unit commitment (\$10.70/MWh of wind).²³

4.1. Balancing cost from electricity markets

In Finland and Sweden, the balancing costs as payments for wind power producers have been estimated from the balancing market (Nordic regulating market) prices to be 0.3–1.4 €/MWh depending on how distributed the wind power is and on the market price level for balancing.^{24,25} In Sweden, the use of 15 min operating reserves has been estimated to increase by 18–56% of current amounts due to wind power forecast errors 1 or 4 h ahead for 4000 MW wind power (8% of gross demand).²⁶ The increased cost of system imbalances of Finland due to future wind power prediction errors was estimated to be 0.2–1 €/MWh for penetration levels of 1–10% of gross demand, assuming the Nordic balancing market was available (no bottlenecks).²⁷

The use of an intra-day market to help reduce the imbalance costs of wind power has been examined in Germany,²⁸ and in Finland²⁹ and Sweden²⁵ for the Nordic market. They have shown that for the current price assumptions and lower penetration levels, there is not a straightforward benefit to use an intra-day market. This is because trading at an intra-day market would mean correcting all potential imbalances due to wind power forecast errors separately, whereas the imbalance payments only apply to the imbalances that affect the power system net imbalances. As wind imbalances are not 100% of the time to the same direction (up or down) as system net imbalances (at low wind penetrations only 50% of the time), this results in less payments.

4.2. Storage

The value of storage in the power system operation in the UK was estimated to be 252–970 £/kW.⁷ For Germany, a 27 M€/year revenue could be foreseen for 400 MW CAES (250 M€ investment).²⁸ In the Netherlands, international exchange was seen as a more promising alternative to storage in the system.²¹ In Ireland, adding storage did not bring additional value in the All Island Grid Study results.²²

For wind penetration levels of 10–20% of gross demand in power systems, the cost effectiveness of building new electricity storage is still low (excluding hydropower with large reservoirs and some pumped hydro). With higher wind penetration levels, the extra flexibility that storages can also provide will be beneficial for the power system operation, provided they are economically competitive with other forms of flexibility. It is important to notice, however, that any storage should be operated according to the needs of aggregated system balancing. It is not cost-effective to provide dedicated back-up for wind power in large power systems where the variability of all loads and generators is effectively reduced by aggregating, in the same way that it is not effective to have dedicated storage for outages in a certain thermal power plant, or having specific plants following the variation of a certain load.

5. TRANSMISSION PLANNING AND COSTS

With current technology, new wind power plants are able to meet system operator expectations, such as riding through voltage dips, supplying reactive power to the system, controlling terminal voltage, and participating in system operation with output and ramp rate control. Grid reinforcement may be needed for handling larger power flows and maintaining a stable and adequate voltage profile, and is commonly needed if new generation is installed in weak or congested grids far from load centres, or where no grid exists, such as offshore.

Transmission cost is the extra cost in the transmission system when wind power is integrated. Either all extra costs are allocated to wind power, or only part of the extra costs are allocated to wind power—grid reinforcements and new transmission lines also benefit other consumers or producers often, and can be used for many purposes, such as increase of reliability and/or increased trading. The cost of grid reinforcements due to wind power is, therefore, very dependent on where the wind power plants are located relative to load and on the grid infrastructure, and one must expect numbers to vary from country to country. Grid reinforcement costs are, by nature, dependent on the existing grid. The costs vary with time and are dependent on when the generator is connected. After building some lines, several generators can often be connected before new reinforcement needs occur. After a certain time, new lines, substations or something else is needed. The grid reinforcement costs are not continuous; there can be single very high cost reinforcements. Using higher voltages generally results in lower costs per MW transported, but this also means that there are even higher increments of capacity and grid costs. The same wind power plant, connected at different times, may therefore lead to different grid reinforcement costs. For transmission planning, the most cost-effective solution in cases that require considerable grid

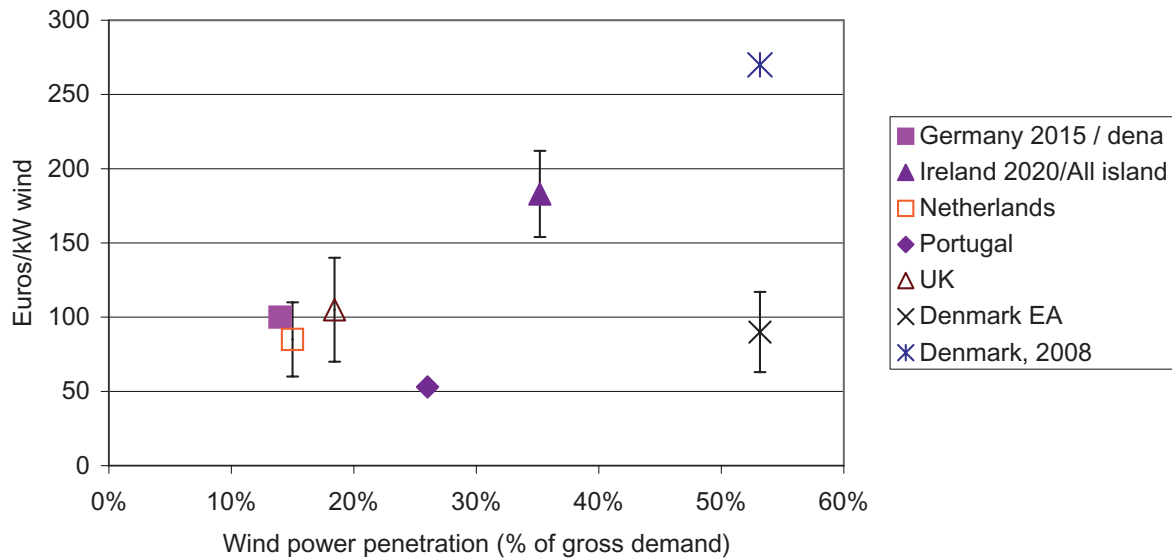


Figure 6. Comparison of the estimated costs for grid reinforcement costs due to wind power. For Denmark, the cost of increasing wind penetration from 20% to 50% is allocated to added wind power. For Ireland the range comes from allocating the cost for all renewables from 0% penetration and for allocating the cost for added renewables (from 2.25 GW to 6.6 GW).

reinforcements would be to build the transmission network for the final planned amount of wind power in the network instead of having to upgrade transmission lines in several phases.

The reported results in the national case studies for grid reinforcements presented in Figure 6 are: UK,¹⁴ the Netherlands,³⁰ Portugal³¹ (lower cost allocating only the proportion related to the wind program of total cost of each grid development or reinforcement) Germany,⁸ Ireland,²² Denmark³² (allocating about 40% of total grid reinforcement cost to wind power) and Denmark³³ (2250 MW of additional off-shore wind power in 2025, excluding the costs of getting the offshore production on shore and no additional network reinforcement costs for increasing onshore wind power with 700 MW from 2007 to 2025).

The grid reinforcement costs from studies in this report vary from 0 €/kW to 270 €/kW. In the USA, a recent study reviewed a sample of 40 detailed transmission studies from 2001 to 2008 that have included wind power.³⁴ The range of transmission costs for wind investigated in these studies ranged from \$0/kW to over \$1500/kW. The majority of studies, however, have a unit cost of transmission that is below \$500/kW and a median cost of \$300/kW. One interesting finding in the USA is that unit transmission costs of wind do not appear to increase significantly with higher levels of wind penetration. When accessing large, remote resource areas, the decreased per unit costs of higher voltage transmission lines and an economics based transmission planning process enable a cost effective solution to be provided to move large blocks of remote wind energy to load centres.

It is also important to note that grid reinforcements should be held up against the option of controlling wind output or altering operation of other generation in cases where grid adequacy is insufficient only part of the time or for only some production and load situations.

The results from the UK³⁵ suggest that at higher penetration levels, requiring sufficient fault ride through capability for large wind power plants is economically efficient compared with modifying the power system operation for ensuring power system security in the case that wind farms do not have fault ride through capability. In stability studies of the Iberian Peninsula, it is shown that to reach penetration levels of more than 10%, fault ride through capability is required in the majority of wind power plants. Also, the German studies conclude that a passive fault ride through capability will not be sufficient in the future. In addition, the turbines have to be able to provide reactive power to the grid. In a US study, it was found that wind power plants with some dynamic reactive capability may reduce or eliminate the need for dynamic reactive devices on the transmission system.³⁶

Dynamic line ratings, taking into account the cooling effect of wind together with temperature in determining the transmission constraints, can increase transmission capacity from the North to the middle of Germany by 40 to 90% at times when the German wind power generation is above 75% of the installed capacity. In 99% of the time, the increase is above 15% for all lines, except some very unfavourable cases, where only an increase of 5% is calculated.³⁷

A Norwegian study shows that the power smoothing effect of geographically dispersed wind power plants gives a significant reduction of discarded wind energy in constrained networks, compared to a single up-scaled wind power plant

site.³⁸ Studies in Norway^{39,40} and Sweden,⁴¹ show that coordination of hydro and wind generation in a region with limited export capability can reduce the need for grid upgrades. These studies also show that with comparatively high costs for grid reinforcements, it can be economically preferable to spill some few percentages of the annual wind or hydro generation as an alternative to increase the transmission capability. Generally, a power system without any grid bottlenecks can be said to have excess grid capacity, hence, not economic. Severe grid bottlenecks should, of course, be avoided.

6. CAPACITY VALUE OF WIND POWER

Wind generation will also provide some additional load-carrying capability to meet forecasted increases in system demand or power plant decommissioning. The analyses for system generation adequacy are made several weeks, months or years ahead, and associated with static conditions of the system. This can be studied by a chronological generation-load model that can include transmission and distribution capacities and constraints, or by probabilistic methods. The data required to make the required generation estimation includes the system demand and the availability data of generation units. There are several approaches used in the literature. Calculating the effective load-carrying capability (ELCC) by determining the Loss-of-Load-Probability of the power system for different load levels is the most rigorous methodology available. Although the use of alternative, simplified methods appears to be somewhat popular, many of these have not been compared to the more robust approaches based on reliability analysis. We strongly encourage this comparison so that the trade-offs of using simplified approaches are transparent.

The results presented in Figure 5 for capacity value of wind power are from Germany,⁸ Ireland,⁴² Norway,³⁹ the UK,¹⁴ Minnesota, USA,^{9,16} New York, USA,²³ and California, USA.¹⁷

The capacity value of wind power has been estimated to be up to 40% of installed wind power capacity if wind power production is strongly correlated with times of high load, and down to 5% in higher penetration scenarios or if local wind characteristics correlate negatively with the system load profile. Aggregating larger areas benefits the capacity credit of wind power.⁴³

Results for the capacity credit of wind power in Figure 7 show a considerable spread. One reason for different resulting levels arises from the wind regime at the wind power plant sites and the dimensioning of wind turbines. This is one explanation for low German capacity credit results shown in Figure 7. For near zero penetration level, all capacity credit values are in the range of the capacity factor of the evaluated wind power plant installations. The positive correlation of wind and load is very beneficial, as can be seen in the case of New York, USA offshore capacity credit being 40%.

An important issue is whether wind power owners will be paid for the capacity value or not. This is also an issue for other types of power plants and depends on the market regulation. Some reports use the term 'capacity cost'. The definition of this term is the cost for compensating the difference in capacity value for wind power and capacity value for a conventional power plant. This 'capacity cost' is not in widespread use now, but it is important to note that when it is calculated, this compensation should be added in cheaper power plants [like open cycle gas turbines (OCGT)]. This is

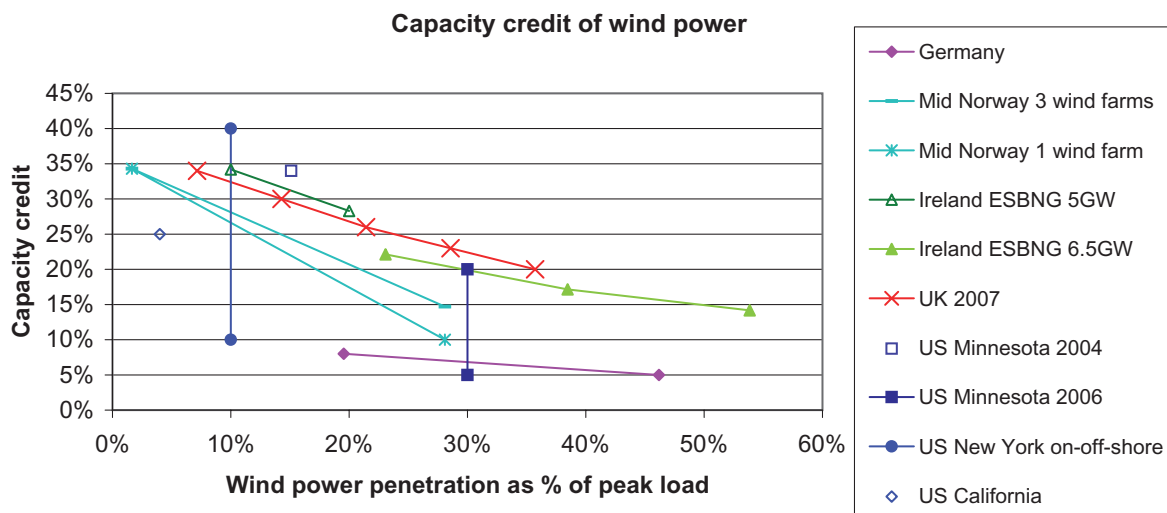


Figure 7. Capacity credit of wind power, results from eight studies. The Ireland estimates were made for two power system configurations, with 5 GW and 6.5 GW peak load.

because the capacity credit is normally calculated for a system where there is danger for capacity deficit only during a time period in the range of hours per year or less. If the capacity credit is not high enough then it is necessary to install extra capacity, but then this extra capacity is only used for a limited number of hours per year. With this level of utilization, OCGTs are preferred. These units have comparatively low investment costs. An alternative is to use voluntary load reduction. Both these alternatives have comparatively low capacity costs.⁴⁴

7. RECOMMENDATIONS FOR WIND INTEGRATION STUDIES

In wind integration studies, it is very important to take the variability of wind into account in the proper way. The variability will smooth out to some extent if there is geospread wind power, and part of the variability can be forecast. Because of spatial variations of wind from turbine to turbine in a wind power plant—and to a greater degree from wind power plant to wind power plant—a sudden loss of all wind power on a system simultaneously due to a loss of wind is not a credible event. A sudden loss of large amounts of wind power due to voltage dips in the grid can be prevented by requiring fault-ride-through from the turbines.

Recommendations for wind integration studies include:

- capturing the smoothed out variability of wind power production time series for the geographic diversity assumed and utilizing wind forecasting best practice for the uncertainty of wind power production;
- examining wind variation in combination with load variations, coupled with actual historic utility load and load forecasts;
- capturing system characteristics and response through operational simulations and modelling;
- examining actual costs independent of tariff design structure; and
- comparing the costs and benefits of wind power.

In most cases, the question is whether extra investments in power systems are economically profitable or not in the new system with a larger amount of wind power—not only stating that a certain amount of extra reserve capacity and/or new transmission lines, etc. are a prerequisite in order to build any wind power.

For high penetration levels of wind power, the optimization of the integrated system should be explored. Modifications to system configuration and operation practices to accommodate high wind penetration may be required. Not all current system operation techniques are designed to correctly incorporate the characteristics of wind generation, and surely were not developed with that objective in mind. Increasing power system flexibility through such means as transmission to neighbouring areas, generation flexibility, demand side management and optimal use of storage (e.g. pumping hydro or thermal) in combination with market aggregation and market or system operation closer to real time will impact the amount of wind that can be integrated cost effectively.

Regarding capacity value of wind power, the recommendations are:

- The availability of high quality chronological synchronized data that captures the correlation with load data is of paramount importance and the robustness of the calculations is highly dependent on the volume of this data.
- Approximations should be avoided, and a full ELCC calculation is the preferred method. Great care and attention are needed when approximations are used. It is challenging to compare capacity credits derived in different studies if different definitions are used.^{44,45}
- In some reports, the term ‘capacity cost’ is used. The meaning of this is the cost for the difference between capacity credit for wind power and capacity credit for a conventional power plant. It is then important to consider the lowest realistic cost compensation in order not to overestimate this cost.⁴⁴

8. SUMMARY AND FUTURE WORK

Several issues that impact the amount of wind power that can be integrated in a power system have been identified. The aggregation benefits of large areas help in reducing the variability and forecast errors of wind power, as well as in pooling more cost-effective balancing resources. An alternative to large balancing areas is to allow and promote intra-day and intra-hour trading within and between different balancing areas in order to obtain low-cost balancing services. System scheduling and operating electricity markets at less than day-ahead time scales help reduce the forecast errors of wind power that affect operating reserves. Transmission is the key to aggregation benefits, electricity markets and larger balancing areas.

Wind integration has mainly been studied up to wind penetration levels of 10–20% of gross demand (up to 50% of peak load), with some first efforts to study higher penetration levels of 40–50% of gross demand.^{19,20,22} What happens at

larger penetration levels, where wind becomes a more dominant part of the power system, is still not completely clear. Studies will have to cover larger interconnected areas to take the cross border transmission into account properly.⁴³ The future power systems may also provide different options for flexibility from the demand side that do not exist today. Future integration studies should take into account the foreseen larger penetration of solar PV or ocean power, which may help smooth the variability of individual technologies. The use of hydro systems with large water reservoirs for storage is likely the most efficient way to balance generation and supply, and for power systems that are linked to such large hydro facilities, this may be a key for economic operation with large penetration of wind generation. This has been studied in IEA Wind Task 24 (http://www.ieawind.org/Annex_XXIV.shtml), and there are still several unresolved issues that should be addressed in future studies.

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