

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

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**Abstract--** 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 power impacts on power systems, with analyses and guidelines on methodologies. There are dozens of studies made and ongoing related to wind integration, however, the results are not easy to compare. 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 large 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.

**Index Terms**—wind integration, grid integration, balancing

## I. INTRODUCTION

ADDITION 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.

### A. 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 system wide impacts have been divided to three focus areas: Balancing, Adequacy of power and Grid (Fig 1). In this international collaboration (IEA WIND Task 25; [www.ieawind.org/AnnexXXV.html](http://www.ieawind.org/AnnexXXV.html)),

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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 (frequency activated reserve; regulation) and secondary reserve for reserves activated in 10...15 minutes (minute reserve; load following reserve).

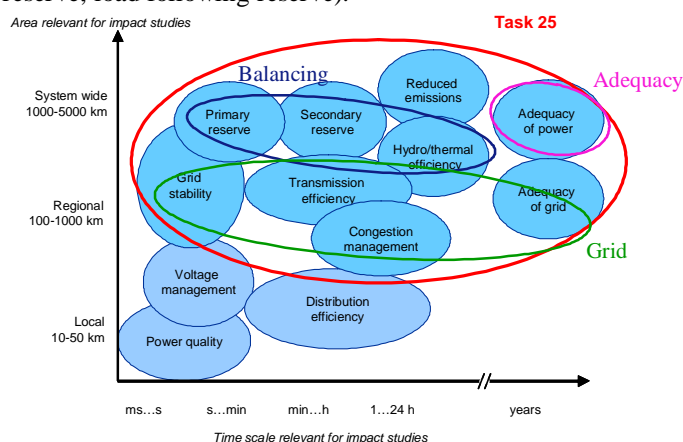


Fig. 1 Impacts of wind power on power systems, divided in different time scales and width of area relevant for the studies.

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 9-20 % of wind energy (of yearly electricity demand) 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 centers for distributed energy that convey data to TSOs and even can react to control needs. Suitable grid codes help to further increase the penetration level: Germany, Denmark, Spain and Portugal have implemented fault-ride-through

requirements for wind power plants in order to keep a certain level of security of supply.

### B. Integration cost of wind power

Many studies assess 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” include 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 also cost-benefit analysis work is emerging. The benefit when adding wind power to power systems is reducing the total operating costs and emissions as wind replaces fossil fuels. Integration costs of wind power need to be compared to something, like the production costs or market value of wind power, or integration cost of other production forms. A fair comparison between power systems with differing amounts of wind power, should in principle have systems with same CO<sub>2</sub> emissions, reliability, etc. The value of the capacity credit of wind power can also be stated.

### C. Defining wind penetration level

Determining what is “high” penetration of wind power is not straightforward. Often either energy or capacity metrics are used: wind power production as % of gross demand (energy) and wind power as % of peak load (capacity). The power systems and highest wind penetrations presented in the case studies are summarised in Fig. 2.

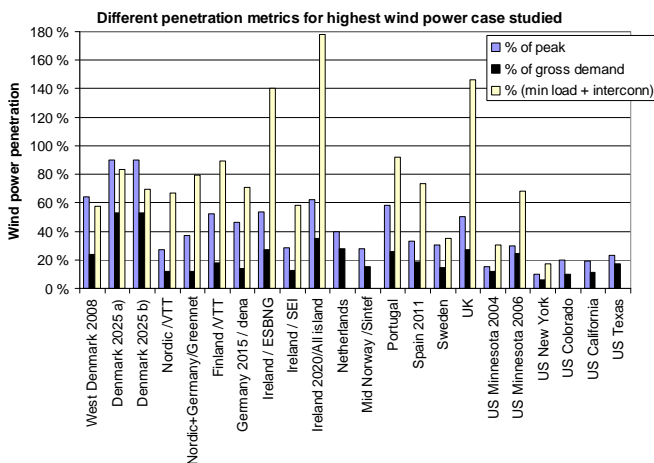


Fig. 2 Comparison of the share of wind power in the power system (penetration levels) studied. For studies covering several countries, the aggregate penetration level has been calculated. Individual countries within the study cases can have significantly higher wind power penetration levels.

To determine high penetration for a power system also interconnecting capacity needs to be looked at. This is because critical moments of high wind and low load can be

relieved by using interconnector capacity, assuming that the neighbour can cope with the additional import. In Fig 2 it can be seen 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.

## II. INCREASE IN SHORT TERM RESERVE REQUIREMENTS DUE TO WIND POWER

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

### A. Methodology

The increase in short term reserve requirement is mostly estimated by statistical methods combining the variability or forecast errors of wind power to that of load and investigating the increase in the largest variations seen by the system [2]. Usually margins for “possible” extreme situations are kept. 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 to that, 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 begin to use probabilistic approaches to define a suitable level of reserves.

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

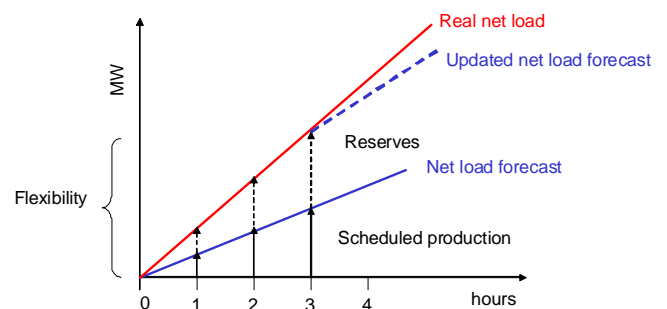


Fig. 3 Flexibility in the power system to follow varying load and wind production (the net load) consists of scheduled production and reserves.

The need of flexibility is not the same as need of reserves, since a part of the net load variation can be forecasted.

### B. Results from studies

The results presented in Fig. 4 for increase in reserve requirements due to wind power are from following studies: Finland and Nordic [4]; Sweden [5]; Ireland [6]; UK [7]; Germany [8]; Minnesota 2006 [9] and California [10].

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 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 hour 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.

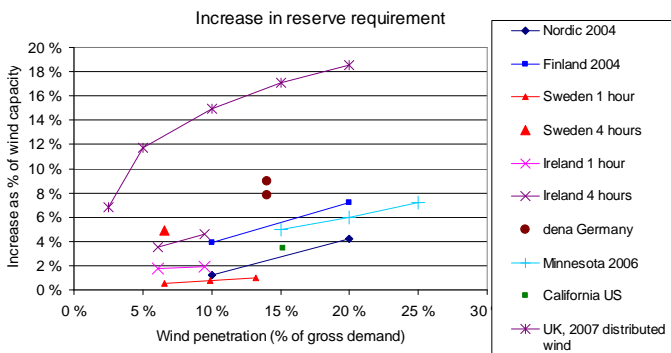


Fig. 4 Results for the increase in reserve requirement due to wind power. German Dena estimates are taking into account the day-ahead uncertainty (for up and down reserves separately) and UK the variability of wind 4 hours ahead. In Minnesota and California, day ahead uncertainty has been included in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

The highest results in Fig 4 are from a study where four hour variability of wind (not forecast error), combined with load forecast error, 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 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 larger increase in reserve requirement than shown here. Swedish TSO published estimates that are 35–48 % of installed wind capacity. This is due to adding up several cases and time frames of reserves. However, the different time frames, for example one hour ahead and four hours ahead, are strongly overlapping. If one has enough flexibility for 4 hours, then this in general implies that during this period there is enough flexibility for 1 hour 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 different units.

An important issue is that “increase in reserve requirements” does not necessarily mean need of new investments. The amount of wind-caused reserves is at highest when wind power is on a high production level. In these situations the other power stations are operated on a low level, which means that 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 is an issue of ramp rates and start-up times, together with a need of more capacity. More fast ramping and starting capacity can 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.

### III. 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 increase in balancing requirement will depend on region size relevant for balancing, initial load variations and how distributed wind power is sited. Here also the operational routines of the power system are relevant – how often the forecasts of load and wind are updated, for example.

#### A. 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 Minnesota [9] 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 optimised when wind power production is added). 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 [12] has been further processed to form a check-list for the national studies that have used simulations [1]. The check-list 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.

### B. Results from studies

The results presented in Fig. 5 for increase in balancing costs due to wind power are from following studies: Finland and Nordic countries [4]; UK [14],[7]; Ireland [6]; Colorado [15]; Minnesota [16],[9]; California [17]; PacifiCorp [18]; Nordic countries and Germany [12].

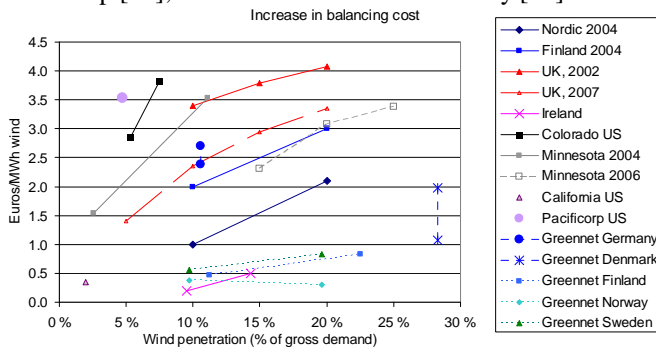


Fig. 5 Results from estimates for the increase in balancing and operating costs due to wind power. The currency conversion used here is 1 € = 0.7 £ and 1 € = 1.3 US\$. For UK, 2007 study the average cost is presented here, the range in the last point for 20 % penetration level is from 2.6 to 4.7 €/MWh.

From the cost estimates presented in 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 wind power produced (Fig. 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 operating the power system closer to the delivery hour with accurate forecast systems.

The highest estimates of reserve requirements from Germany and 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 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 in Fig. 5. The balancing cost paid by the wind power producers is not the same as increase in technical cost of balancing for the 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 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 allowed to be used also for balancing purposes, then the balancing costs are lower compared to the case where they are not allowed to be used.

### IV. 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] and [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: CCGT during peak demand and base-load coal during low demand [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 cost component was not published as such [22].

For New York, 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  $\sigma$  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].



### A. 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] and [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 hours 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 for the Nordic market in Finland [18] and Sweden [25] have shown that for the current price assumptions 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 imbalances, whereas the imbalance payments only apply to the imbalances that affect the power system net imbalances, thus not 100 % of time (at low wind penetrations only 50 % of time).

### B. Storage

The value of storage in the power system operation in 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 NL 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 hydro power with large reservoirs or pumped hydro). With higher wind penetration levels the extra flexibility that also storages can 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 are effectively reduced by aggregating, in the same way as 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.

## V. 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 SCADA system operation with output and ramp rate

control. Grid reinforcement may be needed for handling larger power flows and maintaining a stable voltage, and is commonly needed if new generation is installed in weak or congested grids far from load centers, 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 often benefit also other consumers or producers 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 grid infrastructure, and one must expect numbers to vary from country to country. Grid reinforcement costs are by nature dependent of the existing grid. The costs vary with time and are dependent on the time instant the generator is connected. After building some lines, often several generators can be connected before new reinforcement needs occur. After a certain time instant, new lines, substations or something else is needed. The grid reinforcement costs are not continuous; there can be single very high cost reinforcements. The same wind power plant, connected at different time instant, therefore may lead to different grid reinforcement costs. For transmission planning, the most cost effective solution in cases that demand considerable grid reinforcements would be to build transmission network for the final 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 Fig 6 are: UK [14]; Netherlands: [24]; Portugal: lower cost allocating only the proportion related to the wind program of total cost of each grid development or reinforcement [1]; Germany [8]; Ireland [22]; Denmark: [31] (allocating about 40 % of total grid reinforcement cost to wind power) and [32] for 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.

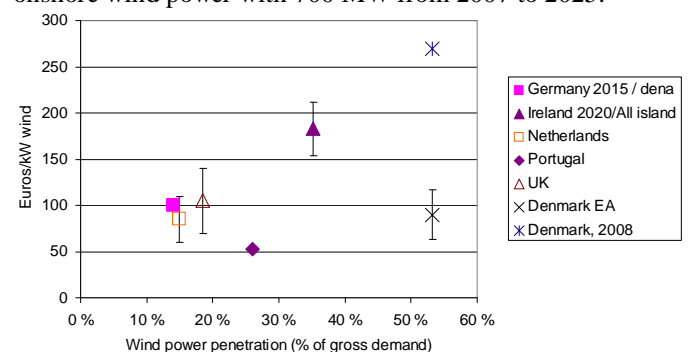


Fig. 6 Comparison of the estimated costs for grid reinforcement costs due to wind power. For Denmark, the cost of increasing wind penetration from 20 % to 50 % is allocated to added wind power. For Ireland the range comes from allocating the cost for all renewables from 0 % penetration and for allocating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

The grid reinforcement costs from studies in this report vary from 0 €/kW to 270 €/kW. In the US, a recent study reviewed a sample of 40 detailed transmission studies from 2001–2008 that have included wind power [33]. 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 US is that unit transmission costs of wind do not appear to increase significantly with higher levels of wind penetration. Economies of scale appear to come into play when accessing large resource areas.

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 during only part of the time or for only some production and load situations.

The results from UK [34] 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 case wind farms are not having 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 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 [35].

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 [36].

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 [37]. In both Norway and Sweden it has been shown that with comparatively high grid costs it can be economically preferable to spill wind power than to increase the transmission capability and that coordination of hydro power and wind power in a region with limited export capability can reduce the need for grid upgrade ([38],[39]).

## VI. CAPACITY VALUE OF WIND POWER

Wind generation will also provide some additional load carrying capability to meet forecasted increases in system demand. 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 literature. Calculating the effective load carrying capability (ELCC) by determining the Loss-of-Load-Probability (LOLP) 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 is transparent.

The results presented in Fig 8 for capacity value of wind power are from: Germany [8]; Ireland [40]; Norway [39]; UK [14]; US Minnesota [9],[16]; US New York [23]; US California [17].

The capacity value of wind power has been estimated to be up to 40 % of installed wind power capacity if wind power production at times of high load is high, and down to 5 % in higher penetrations or if local wind characteristics correlate negatively with the system load profile. Aggregating larger areas benefits the capacity credit of wind power [41].

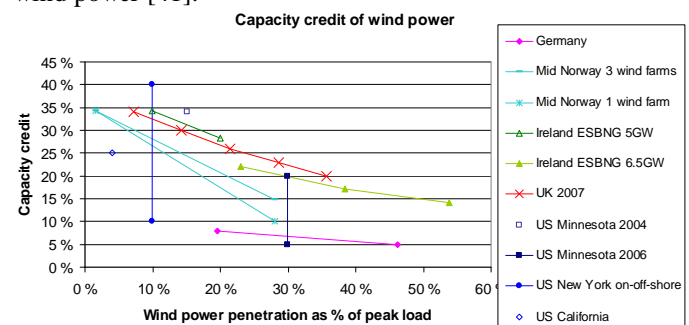


Fig. 7 Capacity credit of wind power, results from eight studies. The Ireland estimates were made for two power system configurations, with 5 GW and 6.5 GW peak load.

Results for the capacity credit of wind power in Fig. 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 Fig. 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 US New York 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 the compensation for the difference in capacity value for wind power and capacity

value for a conventional power plant. This “capacity cost” is not now in widespread use, but it is important to note that when it is calculated this compensation should be added in cheaper power plants (like OCGT). This is 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, perhaps, some hours per year. With this level of utilization, open cycle gas turbines (OCGTs) are to prefer. These units have comparatively low investment costs. An alternative is to use voluntary load reduction. Both these alternatives have comparatively low capacity costs [42].

## VII. RECOMMENDATIONS FOR WIND INTEGRATION STUDIES

It is very important to take the variability of wind into account in a right way in power system studies. 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. 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:

- (i) 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;
- (ii) examining wind variation in combination with load variations, coupled with actual historic utility load and load forecasts;
- (iii) capturing system characteristics and response through operational simulations and modeling;
- (iv) examining actual costs independent of tariff design structure and
- (v) comparing the costs and benefits of wind power.

In most cases the question is whether extra investments to power systems are economically profitable or not in the new system with 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 optimisation 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 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:

- (i) 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.
- (ii) Approximations should be avoided and a full effective load carrying capability (ELCC) calculation is the preferred method and great care and attention is needed when approximations are used. It is challenging to compare capacity credits performed in different studies if different definitions are used ([42],[43]).
- (iii) 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 possible cost compensation in order not to overestimate this cost [42].

## VIII. SUMMARY AND FUTURE WORK

Several issues that impact on the amount of wind power that can be integrated have been identified. Aggregation benefits of large areas help in reducing the variability and forecast errors of wind power as well as help in pooling more cost effective balancing resources. An alternative to large balancing areas is to allow and promote intra-day and intra-hour trading 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 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] and [22]). What happens in larger penetration levels, where wind becomes a more dominating part of power system, is not completely clear. Studies will have to cover larger areas to take the cross border transmission into account properly [41]. The future power systems may also provide different options for flexibility in demand side that do not exist today. Future integration studies should take into account the foreseen high penetration of PV or ocean power. This will help smoothing the variability of individual technologies.

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