State-of-the-art of Design and Operation of Power Systems with Large Amounts of Wind Power, Summary of IEA Wind collaboration

Hannele Holttinen[1], Peter Meibom[2], Cornel Ensslin[3], Lutz Hofmann[4], Aidan Tuohy[5], John Olav Tande[6] , Ana Estanqueiro[7], Emilio Gomez[8], Lennar Söder[9], Anser Shakoor[10], J. Charles Smith[11], Brian Parsons[12] ,Frans van Hulle[13]

[1]VTT Technical Research Centre of Finland; [2]Risoe Technical University of Denmark; [3]ISET, Germany; [4]E.ON Netz, Germany; [5]UCD, Ireland; [6]SINTEF, Norway; [7]INETI, Portugal; [8]University Castilla la Mancha, Spain; [9]University KTH, Sweden; [10]Centre of Distributed Generation and Sustainable Electrical Energy, UK; [11]UWIG, USA; [12]NREL, USA; [13]EWEA

e-mail: hannele.holttinen@vtt.fi

Abstract: An international forum for exchange of knowledge of power system impacts of wind power has been formed under the IEA Implementing Agreement on Wind Energy. The task "Design and Operation of Power Systems with Large Amounts of Wind Power" is analysing existing case studies from different power systems.There are a multitude of studies made and ongoing related to cost of wind integration. However, the results are not easy to compare. This paper summarises the results from 15 case studies.

1 Introduction

The existing targets for wind power anticipate a quite high penetration of wind power in many countries. It is technically possible to integrate very large amounts of wind capacity in power systems, the limits arising from how much can be integrated at socially and economically acceptable costs. So far the integration of wind power into regional power systems has mainly been studied on a theoretical basis, as wind power penetration is still rather limited in most countries and power systems. However, already some regions (e.g. West Denmark, North of Germany and Galicia in Spain) show a high penetration and have first practical experience from wind integration.

Wind power production introduces more uncertainty in operating a power system: it is continuously variable and difficult to predict. To enable a proper management of the uncertainty, there will be need for more degrees of freedom in flexibility in the power system: either in generation, demand or transmission between areas. How much extra flexibility is needed depends on the one hand on how much wind power there is and on the other hand on how much flexibility already exists in the power system.

In recent years, several reports have been published in many countries investigating the power system impacts of wind generation. However, the results on the costs of integration differ and comparisons are difficult to make due to different methodology, data and tools used, as well as terminology and metrics in representing the results. An in-depth review of the studies is needed to draw conclusions on the range of integration costs and constraints for wind power. This requires international collaboration. A new R&D Task titled "Design and Operation of Power Systems with Large Amounts of Wind Power Production" has been formed within the "IEA Implementing Agreement on the Co-operation in the Research, Development and Deployment of Wind Turbine Systems" [1]. The work has started in the beginning of 2006 and will continue for three years. The objective is to analyse and further develop the methodology to assess the impact of wind power on power systems. This R&D task will collect and share information on the experience gained and the studies made, with analyses and guidelines on methodologies. The Task has started by producing a state-of-the-art report on the knowledge and results obtained so far and will end with developing guidelines on the recommended methodologies when estimating the system impacts and the costs of wind power integration. Also, and when possible, best practice recommendations will be formulated on system operation practices and planning methodologies for high wind penetration.

2 Power system impacts of wind power

Wind power has impacts on power system 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), 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).

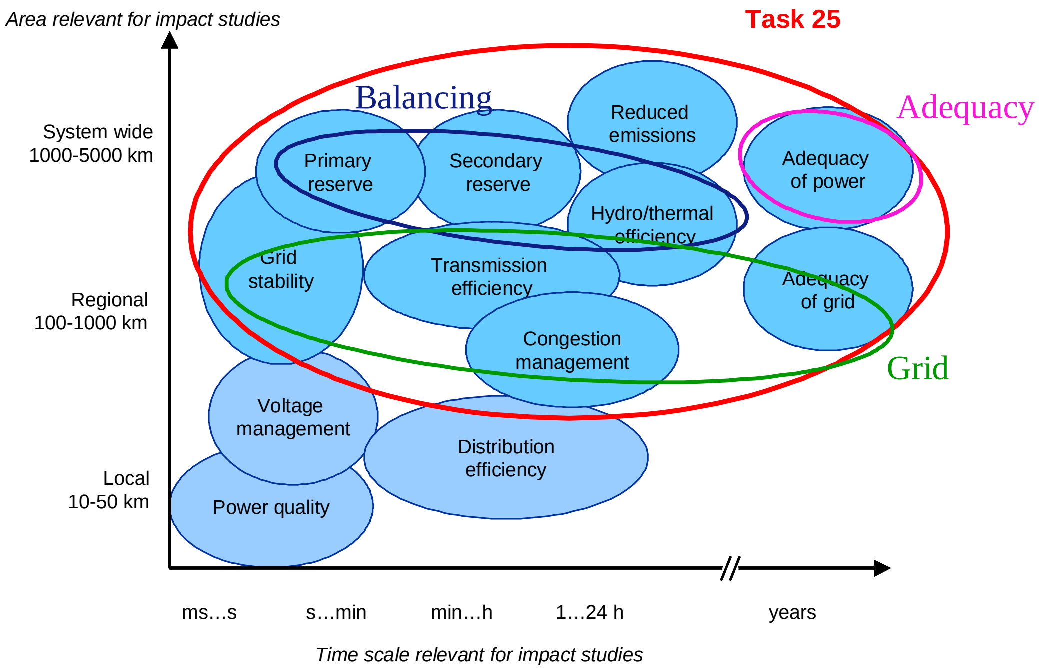

Fig 1. Impacts of wind power on power systems, divided in different time scales and width of area relevant for the studies.

Balancing: increases needed in allocation and use of short term reserves (time-scale minute…half an hour) and the impact of wind variability and prediction errors on efficiency and unit commitment of existing power capacity (time scale: hours…days). Unpredicted part of the variations of large area wind power should be combined with any other unpredicted variations the power system sees, like unpredicted variations in load. General conclusions on increase in balancing requirement will depend on region size relevant for balancing, initial load variations and how concentrated/distributed wind power is sited. The added costs of balancing due to wind power will depend on the marginal costs for providing regulation or mitigation methods used in the power system for dealing with increased variability, generation mix and the transmission system spatial structure (e.g. radial vs meshed). Market rules will also have an impact, so technical costs can be different from market costs. Variability of wind power impacts also on how the conventional capacity is run and how the variations and prediction errors of wind power change the unit commitment. Analysing and developing methods of incorporating wind power into existing planning tools is important in order to take into account wind power uncertainties and existing flexibilities in the system correctly. The simulation results give insight into the technical impacts of wind power, and also the (technical) costs involved.

Adequacy of power: This is about total supply available during peak load situations (time scale: several years). System adequacy is associated with static conditions of the system. The estimation of the required generation capacity needs includes the system load demand and the maintenance needs of production units (reliability data). The criteria that are used for the adequacy evaluation include the loss of load expectation (LOLE), the loss of load probability (LOLP) and the loss of energy expectation (LOEE), for instance. The issue is the proper assessment of wind power's aggregate capacity credit in the relevant peak load situations – taking into account the effect of geographical dispersion and interconnection.

Grid: Transmission adequacy, efficiency and system stability: The impacts of wind power on transmission depend on the location of wind power plants relative to the load, and the correlation between wind power production and load consumption. Wind power affects the power flow in the network. It may change the power flow direction, reduce or increase power losses and bottleneck situations. There are a variety of means to maximise the use of existing transmission lines like use of online information (temperature, loads), FACTS and wind power plant output control. However, grid reinforcement may be necessary to maintain transmission adequacy and security. When determining adequacy of the grid, both steady-state load flow and dynamic system stability analysis are needed. Different wind turbine types have different control characteristics and consequently also different possibilities to support the system in normal and system fault situations. For system stability reasons operation and control properties similar to central power plants are required for wind plants at some stage depending on penetration and power system robustness.

3 Summary of case studies reviewed

For the case studies reviewed in this paper, the emphasis is on more recent studies and especially on those that have tried to quantify the power system impacts of wind power. Further case studies will also be made during the 3 years of the IEA collaboration. A short list of on-going research is given in [2]. A summary table for the power systems and largest wind penetration studied is presented below. A short description of the studies is given here, a more detailed description is provided in [3] and [4].

Table 1. Data for power systems and wind power in case studies.

	Load			Inter-connect. capacity	Wind power					
					2006	Highest studied		Highest penetration level		
Region / case study	Peak MW	Min MW	TWh/a	MW	MW	MW	TWh /a	% of peak load	% of gross demand	% of (min load + interconn)
Nordic 2004	67000	24000	385	3000*	4108	18000	46	27 %	12 %	67 %
Nordic+Germany/Greennet	155500	65600	977	6600	24730	57500	115	37 %	12 %	80 %
Finland 2004	14000	3600	90	1850*	86	4000	8	29 %	9 %	73 %
Germany 2015 / dena	77955	41000	552.3	10000*	20622	36000	77.2	46 %	14 %	71 %
Ireland / ESBNG	5000	1800	29	0	754	2000	4.6	40 %	16 %	111 %
Ireland / ESBNG	6500	2500	38.5	0	754	3500	10.5	54 %	27 %	140 %
Ireland / SEI	6127	2192	35.5	500	754	1950	5.1	32 %	14 %	72 %
Ireland / SEI	6900	2455	39.7	900	754	1950	5.1	28 %	13 %	58 %
Netherlands	15500		100	12930*	1560	6000	20	39 %	20 %	46 %
Mid Norway /Sintef	3780		21			1062	3.2	28 %	15 %	
Portugal	8800	4560	49.2	1000	1697	5100	12.8	58 %	26 %	92 %
Spain 2011	53400	21500	246.2	2400*	11615	17500		33 %	19 %	73 %
Sweden	26000	13000	140	9730*	572	8000	20	31 %	14 %	35 %
UK	76000	24	427	2000*	1963	38000	115	50 %	27 %	146 %
US Minnesota 2004	9933	3400	48.1	1500*	895	1500	5.8	15 %	12 %	31 %
US Minnesota 2006	20000	8800	85	5000	895	5700	21	30 %	25 %	41 %
US New York	33000	12000	170	7000	430	3300	9.9	10 %	6 %	17 %
US Colorado	7000		36.3			1400	3.6	20 %	10 %	

** The use of interconnection capacity is not taken into account in these studies. In Nordic 2004 study the interconnection capacity between the Nordic countries is taken into account.*

Greennet-EU27 [5] estimated increases in system operation costs as a result of increased shares of wind power for a 2010 power system case covering Denmark, Finland, Germany, Norway and Sweden combined with three wind cases. The integration costs of wind is calculated as the difference between the system operation costs in a model run (WILMAR) with stochastic wind power forecasts and the system operation costs in a model run where the wind power production is converted into an equivalent predictable, constant wind power production during the week. The following conclusions could be drawn from the study: a) Wind power integration costs are lower in hydro dominated countries (especially Norway) compared to thermal production dominated countries (Germany, Denmark). The reason is that hydropower production has very low costs connected to part-load operation and start-up and that hydro-dominated systems are generally not constrained in regulating capacity. b) Wind power integration costs increase when a neighbouring country gets more wind power. c) Germany has the highest integration costs because the wind power capacity in Germany is very unevenly distributed with North-western Germany having a high share of wind power relatively to the electricity demand and the export possibilities out of the region.

In Finland the operating reserve requirement due to wind power in the Nordic countries has been estimated in 2004 [6]. The estimate is made from hourly time series for load and wind power, 4 times standard deviation of the variations time series is used as confidence level when looking at the increase in hourly variations from load to net load. The effect of prediction errors day-ahead has not been taken into account; this is only for the real-time hour to hour variations. Existing reserves for disturbances have not been considered; the impact is only estimated on operating reserves used for load following. The increase in reserve requirements for Finland was twice as much as for the Nordic region, due to lower smoothing of wind power variations in one country compared to larger area and the relatively small load variations in Finland. The cost was estimated assuming new natural gas capacity was built for this purpose, and the investment costs was allocated to wind power production. The increase in use of reserves was also estimated and a cost estimate was made at existing regulating market prices of 5-15 €/MWh for imbalances.

A study of 4000 MW wind power in Sweden was published in 2005 [7].The Swedish additional reserve requirements were estimated based on probability and forecast approach, using several years of wind data and load forecast error data. It has been concluded that decisive parameters for the additional requirements are the wind power penetration level and the consumption variations. In power systems with large consumption variations, like the Swedish, lower additional reserves are required compared with power systems with lower consumption variations, like the Finnish. The study indicates that the requirement of additional regulating/reserve capacity is comparatively small, at least for the time horizon 1 hour and with an approach including probability and forecasts. In many cases these extra requirements may also already be available which means that no extra investments are needed.

The main existing study covering wind integration in Germany is German Energy Agency's (dena) study "Planning of the integration of wind energy into the German grids ashore and offshore regarding the economy of energy supply", 2005 [8]. The study ascertained that based on the assessed regional distribution and identified grid reinforcement and extension, the integration of a total of 36 GW of wind power capacity into the German transmission system in 2015 will be possible. Up to the time horizon 2015 approximately 850 km of 380-kV-transmission routes as well as reinforcement of 390 km of existing power lines will be needed. In addition, numerous 380-kV-installations will need to be fitted with new components for active power flow control (e. g. Quadrature Regulators) and reactive power compensation (approximately 7,350 Mvar till 2015). According to this study, a modification of the existing German Grid Code for connection and operation of wind power plants in the high voltage grid will be necessary, for instance in view of fault-ride-through and grid voltage control. Capacity credit of wind power was estimated as well as the additional requirement for reserves. The regulating and reserve power capacity required for the following day was determined in relation to the forecasted wind infeed level. The additionally required regulating energy could be provided by the existing conventional power stations.

Irish TSO ESBNG report 2004 [9]: the wind input assessment methodology used was direct scaling of output data from existing wind power production combined with some planned site wind data to create a power time series. The system assessment methodology was generating system simulation using a unit commitment and dispatch simulator. The study found that a high wind energy penetration greatly increased the number of start ups and ramping for gas turbine generation in the system and that the cost of using wind power for CO2 abatement in the Irish electricity system is €120/Tonne. Capacity credit of wind power was estimated by assessing the amount of conventional plant that is displaced, while keeping generation adequacy at the desired level.

Ireland SEI report from 2004: "Operating Reserve Requirements as Wind Power Penetration Increases in the Irish Electricity System" [10] the wind input assessment methodology was to use a time series generated from statistical manipulation of historic wind power plant data. The system assessment methodology was generating system simulation using a proprietary system dynamic model. The study findings were that fuel cost and CO2 savings up to a 1500MW wind power penetration in the Republic of Ireland (ROI) system were directly proportional to the wind energy penetration. It found that while wind did reduce overall system operation costs it could lead to a small increase in operating reserve costs: 0.2 €/MWh for 1300 MW wind and 0.5 €/MWh for 1950 MW of wind.

Two case studies from UK were taken in review: the ILEX/Strbac report from 2004 [11] and Strbac et al 2007 [12]. Regarding reserve requirements, extra plant may be needed if the existing capacity is insufficient, but the amounts involved are very modest – around 5% of the wind plant capacity, at the 20% penetration level (% of gross demand). Estimates of extra reserve costs from [13] used market costs, which may be expected implicitly to include a capital recovery element. A value of £2.38 per MWh of wind produced for 10% wind penetration is used, rising to £2.65/MWh at 15% and £2.85/MWh at 20% penetration. Historically, transmission costs have been driven by a north-south flow from thermal generators located predominantly in the north, to demand in the south. With significant wind resources in Scotland and off the North West and North East of England and North Wales coasts, it is possible to envisage scenarios where this pattern of flows endures, increasing the requirement for transmission reinforcement and the level of transmission losses. Alternatively, if onshore wind generation were developed across Great Britain and included the offshore wind resources around the England and Wales coast, then transmission reinforcement costs could be significantly smaller. In [13] costs of between £275m and £615m to accommodate 8 GW of wind, i.e. between £35/kW and £77/kW, were found. In [11] the effects of connecting wind power plants at various locations across the country on the transmission reinforcement cost were considered. This included the impact of the locations of new conventional plant and decommissioning of existing generation. The range of cost was found to be between £1.7b and £3.3b for 26 GW wind (£65/kW to £125/kW of wind capacity). Lower values correspond to scenarios with dispersed wind generation connections, with significant proportions of offshore wind around the England and Wales coast, while the higher values correspond to the scenarios with considerable amount of wind being installed in Scotland and North of England. For a small level of wind penetration the capacity value of wind is roughly equal to its load factor, approximately 35%. But as the capacity of wind generation increases, the marginal contribution declines. For the level of wind penetration of 26 GW, about 5GW of conventional capacity could be displaced, giving a capacity credit of about 20% (for a future UK system 70GW peak load and a 400TWh energy demand, and a 35% load factor of wind).

Consequences of 6000 MW offshore wind power for the 150/380 kV grid of the Netherlands were determined by a load flow study. This showed that additional voltage control equipment is required and that a limited number of lines have to be upgraded. Investment costs to the grid were estimated at 344-660 ME, depending on location/scenario (about 4% of est. total investment for 6 GW wind) [14].

For Portugal, in the overall period 2005 – 2010, the investment directly attributable to renewables, mostly for wind parks, will total 200 Million €. These numbers do not consider the investment of the wind park main substation nor the direct line to the transmission network connection point, which are built by the promoter. A study carried out in 2004 by the Portuguese TSO (REN) showed a danger of instability in Portugal + Spain following a short circuit in certain locations of the transmission network. At this moment, REN and its Spanish counterpart REE are completing a second and more detailed joint study with higher wind targets (5100 MW in Portugal and 20000 MW in Spain) that shows also that possibility. The new grid codes with fault ride through were proved to be required, at least at certain parts of the grid.

Different studies, [15-16], were carried out by Spanish and Portuguese TSOs REE and REN to determine the maximum wind power capacity that the Iberian grid could handle. Specifically, the integration of existing wind turbine technologies and future modifications were studied under different scenarios (demand, wind energy production and different degrees of adaptations of new wind turbine and wind power plant technologies). Two scenarios were studied with 17500 MW of installed wind power. Its major conclusions were that with 75% of wind power technically adapted, transient stability was supported for 14000 MW wind power production in a peak demand scenario and 10000 MW wind power production in a valley one. The importance of future 400 KV D/C interconnection line with France was highlighted. In the Spanish case, wind power development has imposed new connecting and operating rules, being the connection and reinforcement costs paid by wind power plants (from the wind power plant to the electrical substation). On the other hand, this has provoked an updating in connecting requirements, protection equipment, remote metering and control, resolution of constraints or wind power plant clustering. Obviously, transmission network must be updated as well; the investment 2200 Million €, not only attributable to renewable, has been estimated by REE for the overall period 2006 – 2010. In terms of investments due to wind energy, it is difficult to obtain the figures for the Spanish case, since grid reinforcements and new lines are needed for wind power plants and other clients (electrical demand growing rates have been high in the last years).

The impact of wind power on system adequacy for one region in Norway was reported in [17]. The impact is assessed using data from a real life regional hydro-based power system with a predicted need for new generation and/or reinforcement of interconnections to meet future demand. Wind power will have a positive effect on system adequacy. Wind power contributes to reducing the LOLP and to improving the energy balance. Adding 3 TWh of wind or 3 TWh of gas generation are found to contribute equally to the energy balance, both on a weekly and annual basis. Both wind and gas improve the power balance. The capacity value of gas is found to be about 95 % of rated, and the capacity value of wind about 30 % at low wind energy penetration and about 14 % at 15 % penetration. The smoothing effect due to geographical distribution of wind power has a significant impact on the wind capacity value at high penetration.

The first Minnesota Dept. of Commerce/Enernex Study (2004) [18], estimated the impact of wind in a 2010 scenario of 1500 MW of wind in a 10 GW peak load system. Three year data sets of 10-minute power profiles from atmospheric modeling were used to capture geographic diversity. Wind plant output forecasting was incorporated into the next day schedule for unit commitment. Extensive time-synchronized historic utility load and generator data was available. A monopoly market structure, with no operating practice modification or change in conventional generation expansion plan, was assumed. Incremental regulation due to wind was found to be 8 MW (at 3σ confidence level). Incremental intra-hour load following burden increased 1-2 MW/min. (negligible cost). Hourly to daily wind variation and forecasting error impacts are the largest cost items. A total integration cost of $4.60/MWh was found, with $0.23/MWh representing increased regulation costs, and $4.37 due to increased costs in the unit commitment time frame. A capacity credit of 26%-34% was found with a range of assumptions using the ELCC method.

The second Minnesota Dept. of Commerce/EnerNerx study (2006) [19] took as a subject power system a consolidation of four main balancing areas into a single balancing area for control performance purposes. Simulations investigating 15%, 20%, and 25% wind energy penetration of the Minnesota balancing area retail load in 2020 were conducted. The 2020 system peak load is estimated at 20,000 MW, and the installed wind capacity is 5700 MW for the 25% wind energy case. Three years of high resolution wind and load data were used in the study. The cost of wind integration ranged from a low of $2.11/MWh of wind generation for 15% wind penetration in one year to a high of $4.41/MWh of wind generation for 25% wind penetration in another year, compared to the same energy delivered in firm, flat blocks on a daily basis. These are total costs and include both the cost of additional reserves, and cost of variability and day-ahead forecast error associated with the wind generation. The cost of the additional reserves attributable to wind generation is included in the wind integration cost. Special hourly runs were made to isolate this cost, which was found to be about $.11/MWh of wind energy at the 20% penetration level. The remainder of the cost is related to how the variability and uncertainty of the wind generation affects the unit commitment and market operation. In the study, the Minnesota balancing authority was assigned responsibility for all the reserves and intra-hour resources for balancing. At the hourly level, the day-ahead markets and in-the-day re-dispatch at the hourly level were administered by MISO for the entire footprint, with an assumed 2020 peak load in excess of 120 GW. Since the real-time market actually operates on five-minute increments, further efficiencies could be obtained if it were assumed that out-of-state resources were available to balance within the hour. Capacity values were investigated and ranged between 5% and 20% for the scenarios studied.

The NYSERDA/GE Energy Study for the New York ISO was completed in 2005 [20]. It estimated the impact of wind in a 2008 scenario of 3300 MW of wind in a 33-GW peak load system. Wind power profiles from atmospheric modeling were used to capture statewide diversity. The study used the competitive market structure of the NYISO for ancillary services, which allows determination of generator and consumer payment impacts. For transmission, only limited delivery issues were found. Post-fault grid stability improved with modern turbines using doubly-fed induction generators with vector controls. 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. Capacity credit was 10% average onshore and 36% offshore. Significant system cost savings of $335- $455 million for assumed 2008 natural gas prices of $6.50-$6.80/MMBTU were found.

The Xcel Colorado/Enernex Study (2006) [21] examined 10% and 15% penetration cases (wind nameplate to peak load) in detail for ~7 GW peak load system. Regulation impact was $0.20/MWh and hourly analysis gave a cost range of $2.20-$3.30/MWh. This study also examined the impact of variability and uncertainty on the dispatch of the gas system, which supplies fuel to more than 50% of the system capacity. Additional costs of $1.25-$1.45/MWh were found for the 10% and 15% cases, bring the total integration costs to the $3.70-$5.00/MWh range for the 10% and 15% penetration cases.

The CA RPS Integration Cost Project examined impacts of existing installed renewables (wind 4% on a capacity basis). Regulation cost for wind was $0.46/MWh. Load following had minimal impact. A wind capacity credit of 23%-25% of a benchmark gas unit was found.

4 Summary of results on increased balancing requirements

Summaries for the results for balancing requirements presented in section 3 are presented in Fig 2 and Fig 3.

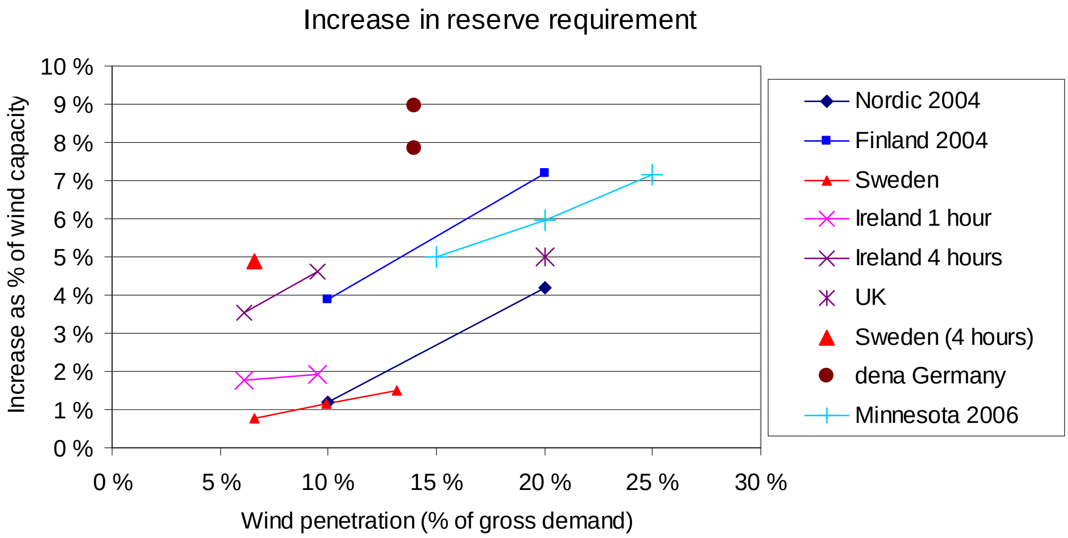

Fig 2. Results for the increase in reserve requirement due to wind power. German dena estimates are taking into account the day-ahead uncertainty (for up and down reserves separately). In Minnesota, day ahead uncertainty has

been included in the forecast. For the others the effect of variations during the operating hour is considered. For UK, Ireland and Sweden the 4 hour-ahead uncertainty has been evaluated separately.

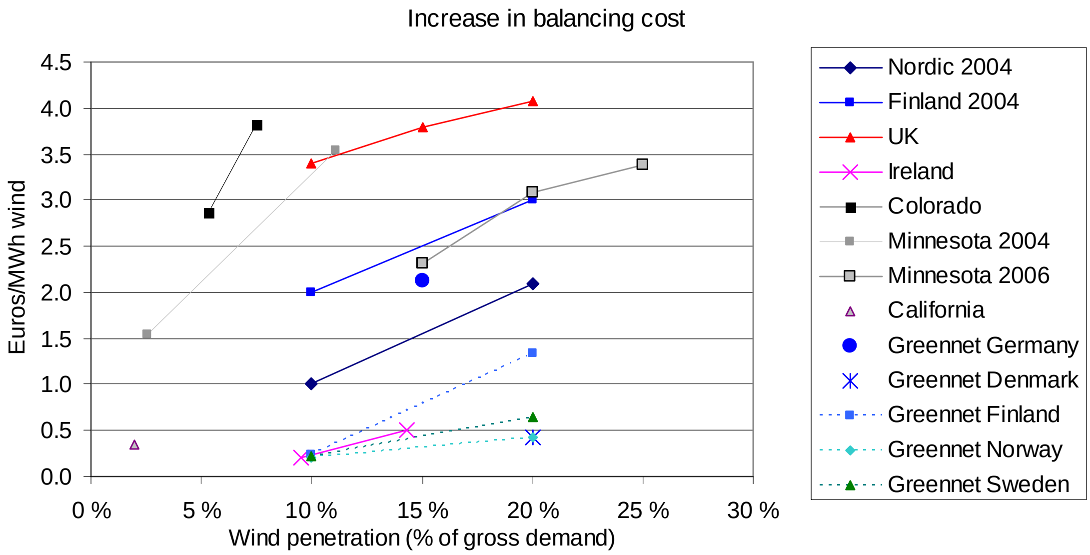

Fig 3. Results from estimates for the increase in balancing and operating costs due to wind power. The currency conversion used here is 1 € = 0.7 £ and 1 € = 1.3 US$.

The increase in reserve requirement is mostly estimated by statistical methods combining the variability of wind power to that of load. In some studies also the sudden outages of production is combined to reserve requirements (disturbance or contingency reserve). For the impact on operation of power systems, model runs are made and 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 and Greennet Nordic+Germany).

At wind penetrations of up to 30% of system peak demand, system operating cost increases arising from wind variability and uncertainty amounted to about 1-4 €/MWh. This is 10% or less of the wholesale value of the wind energy. It can be seen that there is considerable scatter in results for different countries and regions. The following differences have been remarked:

- Different time scales used for estimating – For UK, the increased variability to 4 hours ahead has been taken into account. For US studies also the unit commitment impact for day-ahead scheduling is incorporated. For the Nordic countries and Ireland only the increased variability during the operating hour has been estimated. For the Greennet study, the unit commitment and reserve allocation are done according to wind forecasts but the system makes use of updated forecasts 3 hours before delivery for adjusting the production levels.
- Costs for new reserve capacity investment – For the Greennet and SEI Ireland studies only incremental increase in operating costs has been estimated whereas also investments for new reserves are included in some results (Nordic 2004)
- Larger balancing areas – The Greennet, Minnesota 2006 and Nordic 2004 studies incorporate the possibilities for reducing operation costs through power exchange to neighbouring countries, whereas Colorado, California, German dena study, Sweden, UK and Ireland studies analyse the country in question without taking transmission possibilities into account. The two studies for Minnesota, US show the benefit of larger markets in providing balancing. The same can be seen from the Nordic 2004 results compared with results calculated for Finland alone. Dealing with large wind output variations and steep ramps over a short period of time could be challenging for smaller balancing areas. Larger power systems make it possible for smoothing of the wind variability.

As shown in table 1 the interconnection capacity to neighbouring system is often significant. For the balancing costs it is then essential 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 if they are not allowed to be used. From first review of methodology the other important factors identified as reducing integration costs were aggregating wind plant output over large geographical regions, and operating the power system closer to the delivery hour.

5 Summary of grid results

With current technology, wind power plants can be designed to meet industry 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. In areas with limited penetration, system stability studies have shown that modern wind plants equipped with power electronic controls and dynamic voltage support capability can improve system performance by damping power swings and supporting post-fault voltage recovery. The results of the studies performed in Spain and Portugal suggest that at higher penetration levels, requiring sufficient fault ride through capability for large wind power plants would be economically efficient.

Grid reinforcements may be needed for handling larger power flows and maintaining a stable voltage, and is commonly needed if new generation is installed in weak grids far from load centers. The issue is generally the same be it modern wind power plants or any other power plants. The cost of grid reinforcements due to wind power is therefore very depending on where the wind power plants are located relatively to load and grid infrastructure, and one must expect numbers to vary from country to country. It is also important to note that grid reinforcements in general should be held up against the option of curtailing wind or altering operation of other generation, and these latter options may in some cases prove to be very cost efficient.

For the grid reinforcement, the reported results in the national case studies are:

- UK: £65-125 / kW (85-162 €/kW) for 26 GW wind (20 % energy penetration) and £35/kW- £77/kW for 8 GW of wind
- Netherlands: 60-110 €/kW for 6000 MW offshore wind
- Portugal: from 53 €/kW (only summing the proportion related to the wind program of total cost of each grid development or reinforcement) to around 100 €/kW (adding total costs of all grid development items) for 5100 MW of wind.
- German dena study results are about 100 €/kW for 36 000 MW wind.

The costs of grid reinforcement needs due to wind power cannot be directly compared, they will vary from country to country much depending on location of the wind power plants relative to load centers. The grid reinforcement costs are not continuous; there can be single very high cost reinforcements. Also there can be differences in how the costs are allocated to wind power – for example, in Portugal it has been evaluated how much of the new lines are due to wind power, and only that part of the costs have been allocated to wind.

6 Summary of adequacy/capacity credit results

The capacity credit of wind power answers questions like: Can wind substitute other generation in the system and to which extent? Is the system capable of meeting a higher (peak) demand if wind power is added to the system?

Wind generation will provide some additional load carrying capability to meet expected, projected increases in system demand. This contribution can be up to 40% of installed wind power capacity (in situations with low penetration and high capacity factor at times of peak load), and down to 5 % in higher penetrations or if regional wind power output profiles correlate negatively with the system load profile.

Results for the capacity credit of wind power are summarised in Fig 4. Results of capacity credit calculations 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. For zero penetration level, all capacity credit values are in the range of the capacity *factor* of the evaluated wind power plant installations. This is one explanation for low German capacity credit results shown in Fig. 4. The correlation of wind and load is very beneficial, as can be seen in Fig. 4 in the case of US New York offshore capacity credit being 40 %.

The wind capacity credit in percent of installed wind capacity is reduced at higher wind penetration, but depends also much on the geographical smoothing. This is demonstrated comparing the cases of Mid Norway with 1 and 3 wind power plants. In essence, it means that the wind capacity credit of all installed wind in Europe or the US is likely to be higher than those of the individual countries or regions, even if the total penetration level is as in the individual countries or regions. Indeed, this is true only when assuming that the grid is not limiting the use of the wind capacity, i.e. just as available grid capacity is a precondition for allocating capacity credit to other generation.

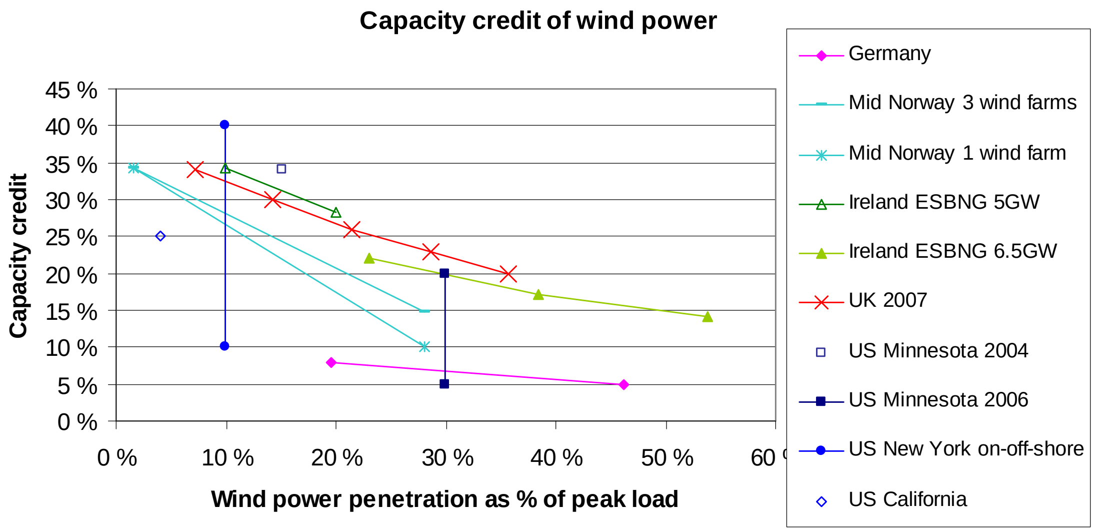

Fig 4. Capacity credit of wind power, results from national studies.

7 Current practice and recommendations so far

Challenges for the case studies include developing representative wind power production time series across the area of study, taking into account the (smoothed out) variability and uncertainty (prediction errors) and then modeling the resultant power system operation. The state-of-the-art best practice so far includes:

- Capturing the smoothed out variability of wind power production time series for the geographic diversity assumed. Use actual data from several wind power plants and met towers, or synchronized weather simulation. Utilize wind forecasting best practice for estimating the uncertainty of wind power production.
- Examining wind variation in combination with load variations, coupling with actual historic utility load and load forecasts. Also the impact of conventional power unit outages can be aggregated.
- Capturing system characteristics and response through simulations and modeling of system operation
- Examining actual technical costs independent of tariff design structure

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. For high penetrations also the surplus wind power needs to be dealt with, e.g. by increasing flexibility in the generation mix, transmission to neighbouring areas, storage (e.g. pumping hydro or thermal) or even demand side management (avoiding wind power curtailment). There is a need to assess wind power integration at the international level, for example to identify the needs and benefits of interconnection of national power systems.

8 Conclusions and discussion

Integration cost can be divided into different components arising from the increase in the operational balancing cost and grid expansion cost. The value of the capacity credit of wind power can also be stated. The case studies summarized in this report are not easy to compare due to different methodology and data used, as well as different assumptions on the availability of interconnection capacity.

Wind generation may require system operators to carry additional operating reserves. Wind's variability cannot be treated in isolation from the load variability inherent in the system. From 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. 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. From first review of methodology some important factors were identified to reduce integration costs, such as aggregating wind plant output over large geographical regions, larger balancing areas, and operating the power system closer to the delivery hour.

With current technology, wind power plants can be designed to meet industry 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 reinforcements may be needed for handling larger power flows and maintaining a stable voltage, and is commonly needed if new generation is installed in weak grids far from load centers. The cost of grid reinforcements due to wind power is therefore very depending on where the wind power plants are located relatively to load and grid infrastructure, and one must expect numbers to vary from country to country. It is also important to note that grid reinforcements in general should be held up against the option of curtailing wind or altering operation of other generation, and these latter options may in some cases prove to be very cost efficient. The results from studies in this paper vary from 50 €/kW to 160 €/kW. The grid reinforcement costs are not continuous; there can be single very high cost reinforcements. Also there can be differences in how the costs are allocated to wind power.

Wind generation will also provide some additional load carrying capability to meet forecasted increases in system demand. This contribution can be up to 40% of installed capacity, 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.

State-of-the-art best practices so far include (i) capturing the smoothed out variability of wind power production time series for the geographic diversity assumed and utilising 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 modelling and (iv) examining actual costs independent of tariff design structure.

Wind resources have impacts that have to be managed through proper plant interconnection, integration, transmission planning, and system and market operations. The issues that impact on the amount of wind power that can be integrated are: aggregation benefits of large areas which mean using transmission possibilities between countries and regions as well as large balancing areas; working electricity markets at less than day-ahead time scales; using and improving wind forecasting. Transmission is the key to aggregation benefits, electricity markets and consolidating balancing areas.

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. It is important to note whether a market cost has been estimated or whether the results refer to technical cost for the power system. There is also benefit when adding wind power to power systems: it reduces the total operating costs and emissions as wind replaces fossil fuels. In this summary only the cost component has been analysed. 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. For high penetrations also the surplus wind power needs to be dealt with, e.g. by increased system flexibility, transmission to neighbouring areas, storage (e.g. pumping hydro or thermal) or demand side management. There is a need to assess wind power integration at the international level, for example to identify the needs and benefits of interconnection of national power systems.

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