IOP Publishing — Environmental Research Letters
Environ. Res. Lett. **3** (2008) 025001 (6pp) doi:10.1088/1748-9326/3/2/025001

Estimating the impacts of wind power on power systems—summary of IEA Wind collaboration

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Received 6 June 2007
Accepted for publication 25 March 2008
Published 28 April 2008
Online at stacks.iop.org/ERL/3/025001

Abstract
Adding wind power to power systems will have beneficial impacts by reducing the emissions of electricity production and reducing the operational costs of the power system as less fuel is consumed in conventional power plants. Wind power will also have a capacity value to a power system. However, possible negative impacts will have to be assessed to make sure that they will only offset a small part of the benefits and also to ensure the security of the power system operation. An international forum for the 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 analyzing existing case studies from different power systems. There are a multitude of studies completed and ongoing related to the cost of wind integration. However, the results are not easy to compare. This paper describes the general issues of wind power impacts on power systems and presents a comparison of results from ten case studies on increased balancing needs due to wind power.

Keywords: wind power, wind integration, integration cost, reserve requirement, balancing cost, grid cost

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. The first practical experience from wind integration comes from regions like West Denmark, the north of Germany and Galicia in Spain.

The transmission grid extensions that wind power requires depend on the location of wind resources relative to load centers. As wind power introduces more uncertainty, the flexibility in power systems either in generation, demand or transmission between areas may have to be increased. How much of an increase (in flexibility) is needed depends on how much wind power there is and 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. A review of the studies is being made as an international collaboration: the R&D Task entitled '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 started at the beginning of 2006 and will continue for three years. The objective is

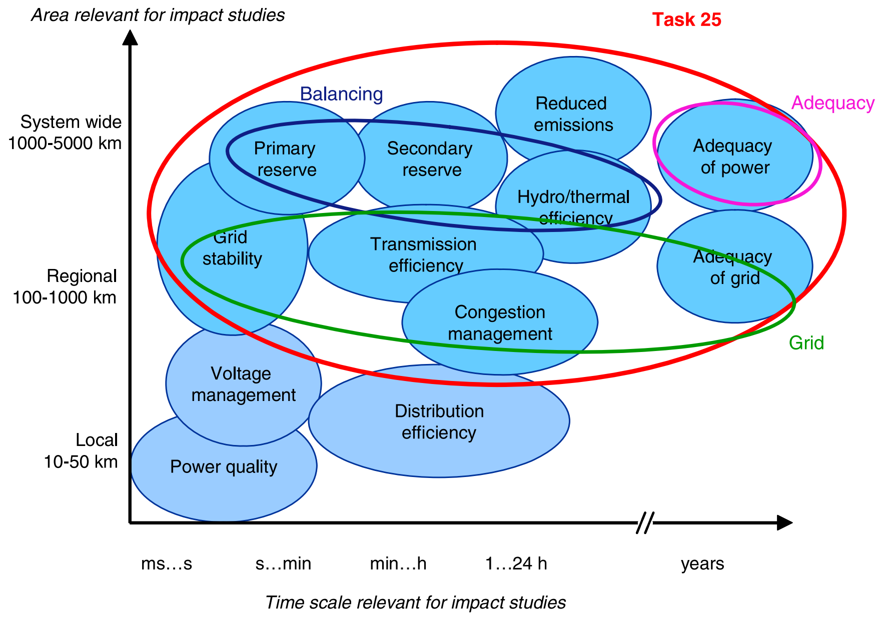

Figure 1. Impacts of wind power on power systems, divided into different timescales and width of area relevant for the studies.

to analyze 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 [2], and will end by developing guidelines on the recommended methodologies when estimating the system impacts and the costs of wind power integration.

The comparison presented in this paper is for more recent studies and for those that have tried to quantify the power system impacts of wind power. Further case studies will also be made during the three years of the IEA collaboration. A short list of ongoing research is given in [3]. A summary of the power systems and largest wind penetration studied is presented below. A more detailed description of the studies is provided in [2] and [4].

2. Estimating the power system impacts of wind power

Adding wind power to power systems will have beneficial impacts by reducing the emissions of electricity production and reducing the operational costs of the power system as less fuel is consumed in conventional power plants. Wind power will also have a capacity value to a power system. However, possible negative impacts will have to be assessed to make sure that they will not offset too large a part of the benefits and also to ensure the security of the power system operation.

The possible impacts of wind power on power system reliability and efficiency are depicted in figure 1, divided into different timescales and how wide the impacts stretch. In this paper the system wide issues are addressed, as opposed to local issues of grid connection like power quality. For estimating the impacts, the different timescales involved usually mean different models (and data) used in impact studies. This is why the case studies for the system wide impacts have been divided into three focus areas: balancing, adequacy of power, and grid.

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. 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. For high penetrations the surplus wind power also needs to be dealt with, for example by increasing the flexibility in the generation mix, transmission to neighboring 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.

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, and reduce or increase power losses and bottleneck situations. There are a variety of means to maximize the use of existing transmission lines like the use of online information (temperature, loads), FACTS (flexible ac transmission systems) and wind power plant output control. However, grid reinforcement may be necessary to maintain transmission adequacy and security. Grid extensions are commonly needed if new generation is installed in weak grids far from load centers. The issue

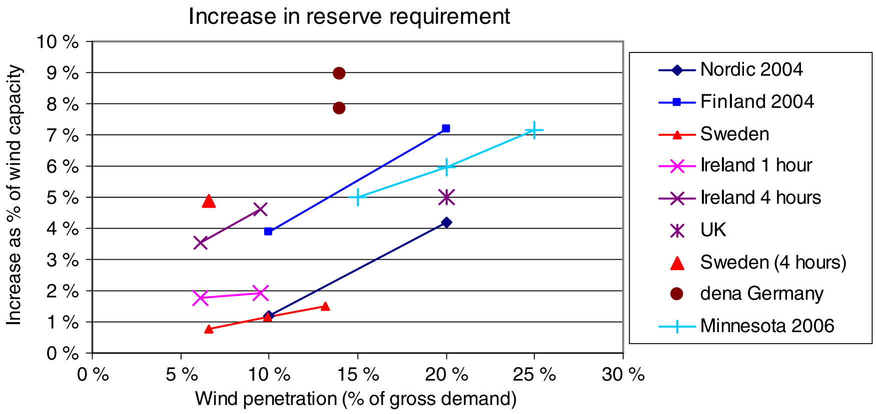

Figure 2. Results for the increase in short term reserve requirement due to wind power. German dena estimates take into account the day-ahead uncertainty (for up and down reserves separately). In Minnesota, day-ahead uncertainty has been included in the forecast. For the others the effect of variations during the operating hour is considered. For the UK, Ireland and Sweden the 4 h ahead uncertainty has been evaluated separately.

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 dependent on where the wind power plants are located relative to the load and grid infrastructure, and one must expect numbers to vary from country to country [4, 11, 7]. 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 (supervision control and data acquisition) system operation with output and ramp rate control.

Power adequacy is associated with static conditions of the system. It is about the total supply available during peak load situations (timescale: several years). The estimation of the required generation capacity needs to include 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), 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. Wind generation will provide some additional load carrying capability to meet expected, projected increases in system demand. This contribution can be close to the average power produced by wind power at times of peak load, when the penetration of wind power is not high, and the capacity value of wind will decrease as wind power penetration increases. Aggregating large areas has a positive impact on the capacity credit of wind power.

Balancing covers the impacts on allocation and use of short term reserves (timescale: minute . . . half an hour) and efficiency and unit commitment of existing power capacity (timescale: hours . . . days). In the timescale of hours to days the positive impacts of wind power can also be seen, reducing the use of fossil fuels thus saving the operational costs of the power system as well as decreasing the emissions. The 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. These issues will be described in more detail in the following section of this paper.

3. Comparing the estimates for wind power impacts on balancing the power system

Summaries for the results for balancing requirements presented in [2] are given in figures 2 and 3. The increase in balancing requirement will be a function of wind penetration level. However, countries and power systems are different in how the variability and unpredictability of wind power will impact the allocation and use of reserves as well as the costs incurred. General conclusions will depend on the region size relevant for balancing, timescale of system operation (how late updated forecasts will be taken into account), initial load variations and how concentrated/distributed wind power is sited. The added costs of balancing due to wind power will depend on the generation mix: marginal costs for providing regulation or mitigation methods used in the power system for dealing with increased variability (figure 3). In many cases the extra requirements for reserves may already be available, which means that no extra investments are needed. Market rules that determine imbalance pricing can have an impact on costs if penalties are applied, so technical costs can be different from market costs. In addition to short term reserve allocation and use, the variability of wind power also impacts how the conventional capacity is run and how the variations and prediction errors of wind power change the unit commitment.

The increase in reserve requirement has mostly been estimated by statistical methods combining the variability of wind power to that of load. In some studies the sudden outages of production are also combined to reserve requirements (disturbance or contingency reserve). For the impact on operation of power systems, simulation model runs are made and most results are based on comparing the 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

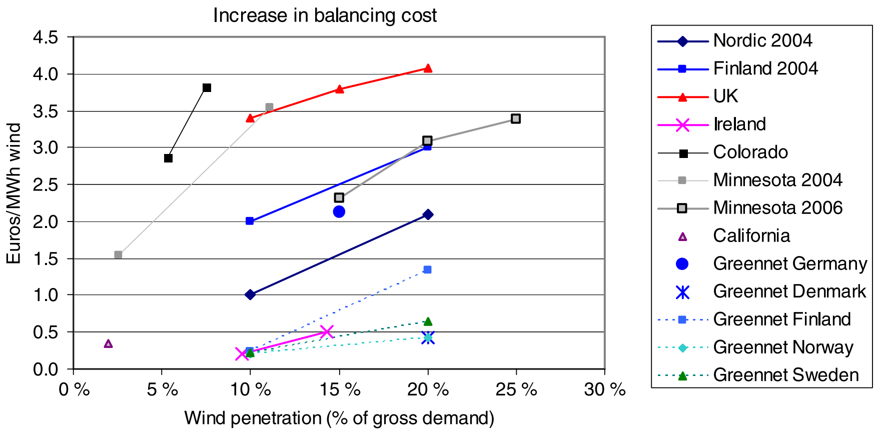

Figure 3. Results from estimates for the increase in balancing and operating costs due to wind power. The currency conversion used here is 1€ = 0.7 £ and 1€ = 1.3 US$.

example in US Minnesota and Greennet Nordic + Germany). The studies referred to in the figures are the following.

- Nordic/Finland 2004: operating reserve requirement due to wind power in the Nordic countries has been estimated in 2004 [5], up to 4 GW of wind in the 14 GW peak system of Finland and up to 18 GW wind in the 67 GW peak system of Nordic countries (10–20% penetration). The methodology is the statistical method combining the standard deviations of wind and load variations time series. When looking at the increase in hourly variations from load to net load 4 times the standard deviation of the variations time series is used as the confidence level (4σ). The estimate is made from three years of synchronous hourly time series for load and (up-scaled) wind power. Only the real-time hour to hour variations are assumed to impact the reserve requirements—the timescale is hourly variations, only. The better predictability of load was taken into account applying load forecast errors instead of load time series (as part of the load variability can be forecasted). The result of the load prediction errors for Finland was assumed for the Nordic case. The cost estimates take into account both the new reserve capacity (according to the amount of increase in reserve requirement, figure 2) and the increased use of reserves (estimated from the duration curves of load and net load variations). If there is no need of increased reserve capacity investment, the cost estimates will reduce to less than half of the results presented here. Estimates were made for the Nordic area assuming similar amounts of wind power in all four countries and separately for Finland. The Finland 2004 results do not take into account the interconnection capacity available.
- Sweden: the Swedish additional reserve requirements for 4–8 GW wind (7–13% penetration) for the 26 GW peak system was estimated based on a similar approach to the Nordic 2004 study, combining the standard deviation of load and wind variation time series. The timescales used were for 1 and 4 h forecast errors separately [6]. Several years of wind data were acquired based on meteorological data, and synchronous load forecast error data were available. No cost estimates were made. The estimates do not take into account the interconnection capacity available.
- Germany: in the German Energy Agency (dena) study [7], the regulating and reserve power capacity requirement due to up to 36 GW wind in 78 GW peak system (14% penetration) was studied. The timescale was day-ahead: the requirement for the following day was determined in relation to the forecasted wind infeed level using statistical methods. The probability density of wind forecast errors was combined with the probability of load forecast errors and outages of conventional power plants. One year of data was used. The additionally required reserve capacity could be provided by the existing conventional power stations so no cost estimate was made. Estimates do not take into account the interconnection capacity available.
- Nordic countries and Germany: the GreenNet-EU27 study [8] 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. The integration costs of wind are calculated as the difference between the system operation costs in a simulation 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. Wind impact on reserve allocation was made in the model combining the probability of wind forecast error to the probability of load and generation variations (outages).
- Ireland: in [9] the operating costs of the 6–7 GW peak system of the Republic of Ireland (2010 scenario) were estimated with up to 2 GW of wind (14% penetration). The wind input was a time series generated from statistical manipulation of historic wind power plant data (half-hourly). The load data was not synchronous. The methodology was generating system simulation for selected days (winter peak, summer valley, shoulder business day). Wind and load forecast errors were combined for different time horizons (1–8 h ahead).

Thermal power was simulated with outages, ramp rates and start/stop costs. Hydro power flexibility was not used in the simulations.

- UK: in [10] and [11] the amounts of extra plant for reserve requirements were estimated at around 5% of the wind plant capacity, at the 20% penetration level (% of gross demand). In [10] estimates of extra short term balancing or reserve costs were not explicitly made in the report. Taking the original values and dividing by produced wind energy resulted in £2.38 per MWh of wind produced for 10% wind, rising to £2.65/MWh at 15% and £2.85/MWh at 20%. Estimates of extra reserve costs used market costs, which may be expected implicitly to include a capital recovery element. Statistical methods of combining wind and load variations were used, and also simulations for selected days were performed to calibrate and to make sensitivity and cost assessments.
- US/Minnesota 2004 and 2006: three-year data sets of 10 min wind 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. Time-synchronized historic utility load and generator data were available. The first Minnesota Department of Commerce/EnerNex Study (2004) [12], estimated the impact of wind in a 2010 scenario of 1500 MW of wind in a 10 GW peak load system. A monopoly market structure, with no operating practice modification or change in conventional generation expansion plan, was assumed. The second Minnesota Department of Commerce/EnerNex study (2006) [13] 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. Incremental regulation and intra-hour load following burden due to wind was estimated at the 3σ confidence level. Hourly to daily wind variation and forecasting error impacts were found to be the largest cost items. For the 2004 study, a total integration cost of \$4.60/MWh was found, where \$0.23/MWh was due to increased regulation. For the 2006 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. The cost of the additional reserves attributable to wind generation is included in the wind integration cost. It was about \$0.11/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.
- US/Colorado: The Xcel Colorado/EnerNex Study (2006) [14] examined 10% and 15% penetration cases (wind nameplate to peak load) in detail for a ∼7 GW peak load system. The regulation impact was \$0.20/MWh and hourly analysis gave a cost range of \$2.20–\$3.30/MWh.
- US/California: The CA RPS Integration Cost Project [15] examined the impacts of existing installed renewables (wind 4% on a capacity basis). The regulation cost for wind was \$0.46/MWh. Load following had minimal impact.

At wind penetrations of up to 20% of gross demand (energy penetration), 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 the results for different countries and regions. The following differences have been remarked upon.

- *Timescales for prediction errors of wind power*—for Nordic 2004 and Ireland only the increased variability during the operating hour has been estimated. For UK, the increased variability to 4 h ahead has been taken into account. For US studies the unit commitment impact for day-ahead scheduling is also incorporated. 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 h before delivery for adjusting the production levels.
- *Costs for new reserve capacity investment*—for the Greennet and SEI Ireland studies only an incremental increase in operating costs has been estimated whereas investments for new reserves are also included in some results (Nordic 2004).
- *Size of balancing areas*—the Greennet, Minnesota 2006 and Nordic 2004 studies incorporate the possibilities for reducing operation costs through power exchange to neighboring countries, whereas Colorado, California, German dena study, Sweden, Finland, UK and Ireland studies analyze 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. Larger power systems make it possible for smoothing of the wind variability.

4. Conclusions and discussion

Adding wind power to power systems will have beneficial impacts by reducing the emissions of electricity production and reducing the operational costs of the power system as less fuel is consumed in conventional power plants. Wind power will also have a capacity value to a power system. However, possible negative impacts will have to be assessed to make sure that they will only offset a small part of the benefits and also to ensure the security of the power system operation. The integration cost can be divided into different components arising from the increase in the operational balancing cost and grid expansion cost.

The case studies conducted in different countries are not easy to compare due to different methodology and data used, as well as different assumptions on the availability of interconnection capacity. Countries and power systems are different in how the variability and unpredictability of wind power will impact the allocation and use of reserves as well as the costs incurred. Grid expansion costs will depend on the strength and extension of the existing grid as well as the location of wind resources versus load centers.

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), the 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. Some studies take into account the impact on short term reserves only, whereas some studies also estimate the impacts of wind variability on how the conventional power plants are scheduled and operated (day-ahead, unit commitment). Some studies take into account costs of building new reserve capacity whereas most studies calculate the increased use of (existing) regulating and reserve power. 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 if they are not allowed to be used. Larger balancing areas allow access to larger balancing resources and the aggregating benefits for wind power (smoothing of variability and reducing forecast errors). Also, operating the power system closer to the delivery hour will reduce the imbalance due to wind forecast errors and lower the negative impacts of wind power.

The 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. 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. There is a need to assess wind power integration at the international level, for example to identify the needs and benefits of the interconnection of national power systems.

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