Int. J. Global Energy Issues, *Vol. 29*, *Nos. 1/2*, *2008* 181

On methodology for modelling wind power impact on power systems

Lennart Söder*

Department of Electrical Engineering,
Royal Institute of Technology,
S-100 44 Stockholm,
Sweden
Fax: (+46)8-790-6510
E-mail: lennart.soder@ee.kth.se
*Corresponding author

Hannele Holttinen

VTT Technical Research Centre of Finland,
FIN-02044 VTT,
Finland
Fax: (+35)8-20-722-7048
E-mail:hannele.holttinen@vtt.fi

Abstract: There is a continuous discussion going on concerning the integration cost of wind power. The integration cost can, for example, be defined as the extra costs in the rest of the system when wind power is introduced, compared with the situation without wind power. The result of the studies depends on both parameters and the method used. The aim of this paper is to structure the methods in order to get some understanding on the impact of different modelling approaches. In general, it can be noted that approximations are always needed since the integration of wind power includes so many complexities including stability of power systems, grid codes, market behaviour, uncertainties and trading possibilities. All these items have to be considered in both the wind power case and in the reference case to obtain an estimation of the integration cost.

Keywords: integration cost; power system simulations; wind energy; wind integration.

Reference to this paper should be made as follows: Söder, L. and Holttinen, H. (2008) 'On methodology for modelling wind power impact on power systems', *Int. J. Global Energy Issues*, Vol. 29, Nos. 1/2, pp.181–198.

Biographical notes: Lennart Söder is currently a Professor in Electric Power Systems at KTH. He is also the Head of the Division of Electric Power Systems. He did his PhD in 1988, entitled on, 'Benefit assessment of wind power in hydro-thermal power systems' and he has been involved in several studies concerning wind power since 1982. His research interest includes power system planning, integration of wind power in power systems, power quality, deregulated electricity market, HVDC, hydropower and reliability. He is the author and coauthor of 115 papers and reports.

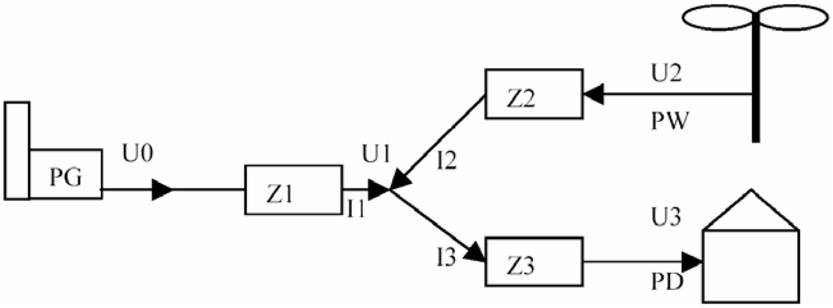
Hannele Holttinen studied at the Helsinki Technical University. Her Masters thesis was on turbulence modelling and her PhD on power system impacts of wind energy. She has been working in VTT Technical Research Centre of Finland since 1989 and she has held various positions such as Research Scientist, Group Manager and Senior Research Scientist. She has been involved in different fields of wind energy research including resource assessment and measurements, production and failure statistics and offshore and arctic wind power feasibility. Since 2000, she has been concentrating on wind power impacts on power systems and electricity markets as her main fields of interest.

1 Introduction

The capacity of wind power has increased by 25–30% per year between 1994 and 2004. This makes wind power the fastest growing energy source. Worldwide, the total installed capacity of wind power has exceeded 50,000 MW during 2005 (*WindPower Monthly*, 2005), which corresponds to an energy production of more than 100 TWh per year. The growth rate is expected to continue bringing the wind power to substantial penetration levels in the power system in several countries and regions. This has led to a continuous discussion on power system impacts and the integration costs of the wind power (DeMeo et al., 2005; EWEA, 2005).

The integration challenge of wind power can be illustrated using Figure 1 (Söder and Ackermann, 2005). In this schematic presentation of a power system, there are industries and households that consume power, PD and a wind power station that delivers power, PW. The remaining power, PG, is produced at another location. The impedances Z1–Z3 represent the impedances in the transmission lines and transformers between the different components.

Figure 1 Illustrative power system



In an electric power system, such as the one in Figure 1, power cannot disappear. This means that there will always be a balance in this system as

$$PG = PD + PL - PW \tag{1}$$

where PG = additional required power production; PD = power consumption; PL = electrical losses in the grid impedances Z1–Z3; PW = wind power production.

Note that pumped hydro and other forms of electricity storage are not listed directly, since such storage may be considered part of PD (when charging) and part of PG when generating. The losses would be included in PL.

Equation (1) is valid for any situation; it does not matter whether we consider the mean value of a minute or the mean value of a year. The most important consequence of Equation (1) is that there is no storage available in the electrical system. This means that if electric consumption changes, electric production must change simultaneously. Automatic controls in both generation units and loads are applied to make this work instantly.

The main aim of a power system is to supply consumers with electricity in an economic and reliable way. The consumers mainly have three requirements (RE):

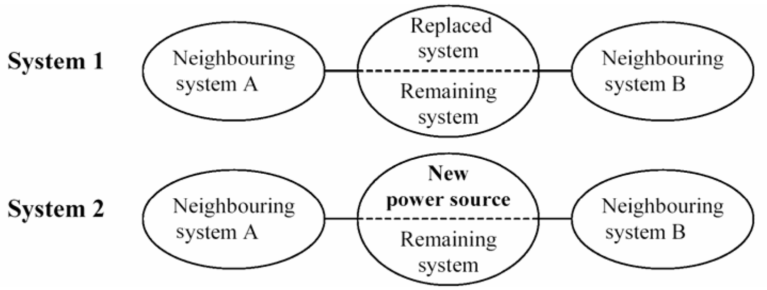
RE1 The voltage at the connection point has to stay within an acceptable range. The reason is that most customer appliances, e.g. lighting equipment, motors, computers, require a specific range, e.g. 230 V ± 10%.

RE2 When the consumers want to use various appliances, the power should be available directly on request, i.e. when a customer switches on a certain device.

RE3 The consumed power should be available at a reasonable cost (this may also include external costs to pay for the environmental impact of electricity production).

RE1 and RE2 concern the reliability of the power supply. There is always a trade-off between costs (RE3, i.e. reduce consumer costs) and reliability; the greater the reliability, the greater the costs. The aim of an integration study is normally to study the consequences of integrating a certain amount of a new power source in a certain system. 'Integration cost' is then defined as the additional costs that are required in the system (except the costs for installing the new power plants) to keep customer requirement, RE1 and RE2, at an acceptable reliability, i.e. R3 (Figure 2)

Figure 2 Integration cost = [costs in system 2] – [costs in system 1]



For further analysis, we first have to define two terms:

The replaced system = The power system consisting of other power sources in the system that will be replaced by the new power source. For example, in Figure 1 PW is the 'new power source', while the replaced system is the decrease in PG because of PW. (2)

The remaining system = The power system consisting of the other power sources, that are the same in both alternative systems (Figure 2) (3)

It is important to note that how the *replaced system* is selected is essential for the result. If the alternative to wind power (i.e. the *replaced system*) is nuclear power that is not taking part in regulation (as the amount of production changes should be kept small), the consequence of having wind power is also smaller compared to if wind power would replace easily regulated gas-fired generation.

Also the selection of the *remaining system* is essential. If wind power is to be integrated in a system with a large share of nuclear power (i.e. the *remaining system*), this will then cause a much larger 'integration cost' compared to a study where the *remaining system* consists of easily regulated gas-fired generation.

There are several methods that have been applied to estimate the wind power integration cost for different systems (Söder, 1994; DeMeo et al., 2004; Holttinen, 2004; dena, 2005; Wilmar, 2005) and also different time scales need to be considered to assess the impacts causing costs. For example, impacts on the energy production of power plants usually involve hourly or weekly time scales whereas impacts on system stability of momentary reserves require seconds or milliseconds as time scale. It is important to stress that all the power systems have to be designed for continued supply of power when any of the generators fail. Therefore established systems will always have many control systems and reserve forms of capacity that can help accommodate the introduction of wind power.

In this paper the following issues and their impact on the result of the integration study will be discussed:

- Is the aim to study the consequence of a certain amount of wind power and/or to find the limit of what is possible? (Section 2)
- Is wind power seen as an extra source that is added to an existing system or is wind power seen as one expansion alternative that is compared with another one? (Section 3)
- How is the imbalance in the power system calculated? Are wind speed forecasts included in the studies? Is it assumed that the accuracy of these is on the best available level? Are imbalances in the load and other production units taken into account when determining the reserve requirements? (Sections 4, 5 and 7)
- How detailed is the description of the power system especially in its flexibility? (hydropower, transmission limits, thermal power; Sections 6, 7, 8 and 9)
- When wind power is expanded, is it assumed that the rest of the system, including the grid, is optimised from the economical point of view or not? (Section 11)
- Is it assumed that the trading rules between neighbouring systems are optimal from the total system economic point of view or are existing rules used? (Section 11)
- Is the integration cost calculated as the 'physical cost' (fuel and investment costs) or is it calculated as the 'market cost', i.e. what different actors can be assumed to get paid? (Section 10)
- Is it assumed that the balancing power is traded on the cost level or on the value level? The formal problem is that wind power owners need balancing (are ready to pay a lot), while the sellers of regulating power wants to maximise their profit. What is then assumed about the pricing of this service? (Section 10)

The aim of this paper is not to evaluate the specific integration cost studies, but more to provide a systematic overview of how different approaches affect the result, from a theoretical point of view. The paper is also organised in such a way so that it is possible to classify a study based on which methods (or combination of methods) are used.

2 Aim of integration study – (A – Aim)

The aim of an integration study is normally to study the consequences of integrating a certain amount of wind power in a certain system. Integration cost has different cost components like additional balancing cost and additional transmission costs. In general, system studies address technical costs, but regulatory/market aspects are also important.

It must be noted that we here use the term 'integration cost', but it could be a negative cost if the wind power had a positive impact on the costs in the remaining system. Concerning the aim of the integration study, there are often two approaches of how to formulate this:

A1 Study the consequences of a certain amount of wind power in a certain system. This is the aim of certain studies such as dena (2005).

A2 Study how much wind power can be integrated in a certain system.

In approach A1 a conclusion can be that it is necessary to do some kind of investments to make it possible to integrate the studied amount of wind power. This means that the resulting 'integration cost' includes both investment costs and increased operation costs in the remaining system.

In approach A2 the aim is more to study the limit within the existing system, i.e. without doing any extra investments. Formally, this means that the customers should still have an acceptable reliability according to the requirement RE3. In a pure A2 approach no investments are done in the remaining system, which means that the 'integration cost' consists of increased operation costs only. It is, of course, also possible to accept some investments (e.g. some transmission lines, but no changes in the power plants) and thereby the 'integration cost' can include also the investment costs in the remaining system. Concerning the aim, a study probably selects A1 or A2; but, as mentioned, an 'adjusted' A2 approach can also include some investments.

3 Different methods to perform an integration study – (M – Methods)

The study can be made in different ways, which will give different results. The basic types of methods are

M1 Increase the amount of wind power with X GWh year^{-1} in a given system. Take, for example, a historical year and increase the amount of wind power in this. This means that the *replaced system* in Figure 2 will consist of some *energy* production in the existing system. This method is used in Söder (1994) and Holttinen et al. (2001).

M2 Replace some existing *capacity*, e.g. a coal power plant with the same yearly energy (X GWh) production, with wind power. This means that the *replaced system* in Figure 2 will consist of these power plants in the existing system; an alternative is also to assume that the load increases with the same amount as, for example, the yearly energy production in the wind power plants. It is necessary to define the alternative to wind power for estimating the 'integration cost'. This alternative is the *replaced system* in Figure 2.

M3 Estimate how an economically efficient system should be configured if the amount of wind power increases by X GWh year^{-1}. Assume, for example, that X GWh year^{-1} of wind power will cause a (wind or water) spillage of Y GWh year^{-1} because of grid limitations. It may then be profitable from the system point of view to increase the grid capacity in order to reduce the spillage from Y to Z GWh year^{-1}. This is profitable if the cost of the grid extension is less than the value of saved fuel, since the increased wind power production of Y–Z GWh year^{-1} will replace fuel somewhere. There are also other alternatives, such as increase the controllability in some other power plants to reduce problems of the X GWh wind power. This method is used, at least for some parts, in dena (2005).

Concerning the methods of performing the study, it is probable that it is of type M1, M2 or M3. It is, however, possible to have combinations of M1, M2 or M3 approaches. One could add wind power without replacing (M1), but change the regulating capacity in a minimum cost approach (M3), i.e. M1 + M3. One could also replace some power plants (M2) and do some parts of replacement in an optimal manner, i.e. M2 + M3.

A consequence in the method M1 is that the risk of capacity deficit decreases since the installed amount of generation capacity increases. A consequence is also that the operation cost in the rest of the system decreases. This method cannot be used in a pure hydro system, unless the load is increased correspondingly, otherwise wind power only will replace water that then will be spilled. M3 represents the most correct method, since it reflects how the system is operated in reality where the different actors adapt themselves to new situations. One can see the method M3 as a dynamical approach where it is assumed that if X GWh of wind power is installed, then the power companies will try to solve the possible problems in an economically efficient way. It can though be noted that 'solving the problems', of course, is a cost, but this cost is less than the costs that incur if the problems are not solved. With the correct market rules, mentioned in Section 11, the actors' behaviour will lead to an economically efficient system.

4 Calculation of imbalance in the system – (I – Imbalance)

Power system operation takes an advantage of large interconnected systems to decrease the net imbalances that have to be regulated. Individual load and generation imbalances cancel out each other to a large extent in a larger area. The operating reserves are used during the operating hour, according to the net imbalances of the whole power system. To estimate the imbalance cost due to wind power, it is crucial to take into account the imbalances in the power system before wind power and only consider the increase due to adding this one component in a large system.

I1 Assume that only the unpredicted wind power will cause imbalance in the power system.

I2 Assume that the forecast errors of both wind power and load will result in net imbalance of the power system.

I3 Assume that the forecast errors of wind power, load and other production units will result in the net imbalance of the power system.

Here I1 and I2 are not correct. However, I2 can be justified, as the load is the most common cause of imbalances together with the wind power when its share is large. Using only the wind power forecast errors would overestimate the balancing needs of wind power in the power system. Only at very large penetration levels, where uncertainties of wind power will dominate the balancing needs, this could give estimates of the right order of magnitude.

Also how many hours ahead the imbalance is calculated has an impact on the increase in balancing needs for wind power. If we consider that only the variability of the wind power during the operating hour causes imbalances (Holttinen, 2005), we get far lower balancing needs for the system than if we assume that all forecast errors of wind power day-ahead will remain uncorrected and cause imbalances during operating hour (dena, 2005). How many hours ahead are needed for the generators to schedule, dispatch and reschedule their production is crucial for the results of balancing needs for the system.

The time-scale resolution needed for these studies is at least hourly, preferably 10 min. For momentary/spinning reserves (primary reserve), the time-scale resolution is seconds to minutes. However, the impact of wind power on the less than minute time scale is very little due to smoothing effects of large-scale production.

5 Location of balancing resources – (B – Balancing)

When a wind power plant is integrated in a system, the balancing procedure (i.e. customer requirement RE2) will change. More wind power (PW in Figure 1) will cause the remaining system to change its production more to keep the balance according to Equation (1). The question is which units are assumed to participate in this balancing? The balancing is activated for the net imbalances of the whole aggregated power system, as long as there is transmission capacity available between surplus and deficit areas. Unpredicted variations of wind power will increase the balancing needed, only if they cause imbalances to the same direction as the unpredicted variations of the load and output of other generation units.

B1 Assume that wind power will be balanced with dedicated sources, e.g. all variation in the new wind power will be balanced with some specific hydropower plants. This makes the study comparatively simple, since all the other parts of the remaining system are run as before. However, this approach does not take advantage of aggregating all imbalances in the power system area (of all loads and generation units) and will overestimate the impact of wind power to the power system. This may be justified when studying the impact of wind power to one producer in trying to keep the production schedules and to avoid imbalance payments. This approach is used by Söder (1994).

B2 Assume that the power system will be balanced with the power plants in the same region (e.g. a country), i.e. keep the same transmission on the lines to neighbouring regions as without the new source. This limits the study to the specific region.

B3 Consider the balancing possibilities also outside the region, where the wind power source is located. Considering these possibilities can decrease the integration cost since balancing resources in neighbouring regions should only be used if this is beneficial from the economical point of view. One study that has used this method is Holttinen (2005).

The approach B3 is most likely to be the best, since it assumes that the electricity market is operated in a rational way. Alternatives B1 and B2 assume both that there are trading limitations in the system. B1 assumes that a specific source has to be used, when there may be other, more cost-efficient, solutions. Alternative B2 does not allow neighbouring systems to participate in the balancing, although this may be a more cost-effective solution.

6 Description of grid, transmission limitations – (G – Grid)

One common consequence of the wind power is the question of grid adequacy, the increased need of transmission and interconnection capacity. In a power system there are always limitations in how much power can be transmitted from one point to another point. The limitations depend on thermal limits, angle stability limits or voltage stability limits. When a future power system is studied where the wind power plants are installed, then this means that power will flow in another way compared to the situation if these new plants are not installed. This means that in some way the transmission limitations should be considered:

G1 Assume that there are no problems in the transmission grid, i.e. neglect all limits. This is usually taken as an approach inside regions that do not have severe bottleneck problems. With this method, usually the impact on transmission losses cannot be estimated.

G2 Consider static MW limits between regions that experience transmission limit or bottleneck situations. Use either a close to maximum MW limit (overestimating the transmission possibilities part of the time) or a lower limit that can happen part of the time (underestimating the transmission possibilities rest of the time). Here some estimates on the transmission losses can be made. The study of Holttinen and Pedersen (2003) has used this approach.

G3 Consider static limits including impact on voltages by performing load flow analysis, where the result is voltage in each node and transmission on each single line.

G4 As G3, but also consider the N-1 criterion, i.e. it must be possible to transfer the required amount of power in the transmission grid when there is an outage of the heaviest loaded line.

G5 Perform full-scale dynamic analysis of the power system for all relevant operation and fault situations. This means that the dynamic behaviour (power oscillations in the range of some Hertz) is included. These type of simulations are necessary to enable the identification of the limits set by angle stability. Details about this method are found in, for example, Bergen (1986). The study by dena (2005) has used this approach in some parts.

G1 and G2 can be applied in models using hourly, weekly or monthly time resolution. For G3 and G4, the time resolution needs to be at least hourly. For G5 the time resolution needed is seconds or less. The most accurate method is G5, but in reality it is impossible to do this kind of simulation for all possible situations, since it will require too much data and computer time. But since this method is closest to the reality, all the other methods must in some way reflect the G5 method. This can be done in several ways by, for example, setting the transmission limits (G2) based on stability margins (obtained with G5 method) for a case with an outage (N-1) in the most important line (G4).

This is a crucial question for most of the studies involving wind power. Using transmission between countries and regions is commonly the most economical way of dealing with increased variability in the area where wind power is installed. When studying the wind power in large interconnected systems like Central Europe, whatever the area in question, there are always interconnections to neighbouring areas. Taking into account all the interconnections between countries makes the simulation model very large to handle. In most cases, a static way of representing transmission at the edge of the area in question will be taken and then the question is whether problems due to variability will remain over- or underestimated.

7 Treatment of uncertainties – (U – Uncertainty)

In the operation of the power system, there are always many uncertainties. These include: possible outages of transmission lines and power plants, changes of load, changes of wind power production, changed amount of inflow to hydropower plants, changed behaviour of different actors, which may result in changed prices. These uncertainties have to be considered to obtain the integration cost of a wind power plant. Some of the uncertainties have a direct link to the market structure of the power system (like gate closure times). It is also important to combine the uncertainties in a correct way, as they often are independent and thus do not add up linearly.

U1 *Uncertainty in transmission limits*. Assume pre-calculated margins for transmission capacities and available power in the production in the remaining system (Section 6).

U2 *Uncertainty of hydropower*. Consider stochastic optimisation concerning the seasonal planning of hydropower systems. This is a common approach in power systems with large amounts of storable hydropower. It is also important to include the capacity factor of hydro, i.e. limitations of rainfall and water supply during winter.

U3 *Uncertainty of wind power*. Consider that there are no wind speed forecasts available. Then one can assume that all the wind power can disappear (= 100% forecast error), which means that spinning reserve margins of full wind power production have to be available. An alternative is to assume perfect wind speed forecasts, but have an approximate estimation about needed reserves, e.g. a certain percent of actual wind power production.

U4 Assume the persistence forecasts of wind power, i.e. a forecast that says that the wind power production next hour(s) will be the same as now. Margins then have to be available in proportion to the possible changes from this level. It must though be noted that when wind power production is large (less production in remaining system), then the margin in the remaining system for upregulation is relatively large since the production in this system is not so large. In situations with small wind power production (relatively large production in remaining system), the risk of large outages in the wind power is low (since the production is not so high) and the reserve requirement is therefore comparatively low. But there may be a considerable need for down-regulating reserve if wind starts blowing.

U5 Assume that the best available forecasts are available for the whole wind power system: for each region with wind power plants. This means that the total forecast error for the whole wind power system is smaller than for one wind farm, since forecast errors in different regions are not 100% correlated. Wilmar (2005), Weber et al. (2004) and Söder (1994) have used this approach.

U6 *Uncertainty of load*. Consider the load forecast errors together with wind power forecast errors to get the reserve need for the total aggregated net system imbalance.

U7 *Uncertainty of thermal power*. Take into account the possibility of sudden failures.

The most accurate method is to combine all uncertainties, U1, U2, U5, U6 and U7, i.e. assume that the companies that will operate the future power system will use the best available tools. It is important to note that the total uncertainty is *not* the sum of the individual uncertainties. It is statistically more reasonable to take the total uncertainty as equal to the root mean square of the individual uncertainties. There is, however, a great challenge to develop a simulation program that can include all these tasks, since the coupling between all continuously updated real values and forecasts (wind, load, prices, available production, inflows, etc.) requires an extended modelling and computer time. Uncertainty of hydropower is seen and can be modelled mostly in the weekly/monthly time scale. This uncertainty can be taken into account either aggregated in trans-national level, which can be enough for describing larger markets in weekly time scales or more detailed in regional level requiring more computational effort and detailed input information. Taking into account the uncertainty of transmission limits means a more detailed time resolution, at least hourly. Wind power brings about uncertainties in several time scales: one that affects unit commitment (some hours), one that affects dispatch/rescheduling (more than some hours), one that affects reserves directly (within an hour).

8 Hydropower plant modelling – (H – Hydro)

In addition to the uncertainties of hydro inflow discussed in Section 7, hydropower plants have several parameters that are important for their possibilities to participate in the needed balancing in the power system. These include varying efficiency, hydrological constraints in rivers with several hydropower stations, head height dependent power production in hydropower stations, etc. When an integration study is performed, this has to be considered in some way.

H1 Consider the head height depending power production for hydropower plants.

H2 Consider the hydrologic coupling between hydropower plants in the same river.

H3 Consider the hydrologic/flow restrictions.

H4 Availability of water, capacity factor, dry/wet year.

The best method is to use all these models at the same time, i.e. H1 + H2 + H3 + H4. This is possible if the region simulated is not too large and time resolution (Section 11) not too short. But to do this for hydro-dominated power systems with many river systems, in combination with the consideration of uncertainties (Section 7) and shorter timer resolutions (an hour or shorter), is a big challenge, especially if one wants to have computer solutions within a realistic time frame.

9 Thermal power plant modelling – (T – Thermal)

Thermal power plants have several parameters that are important for their possibilities to participate in the needed balancing in the power system. These include ramp rates, varying efficiency, start-up times, forbidden operation points, coupling to heat production in Combined Heat and Power (CHP) units, etc. There are significant differences between thermal steam plant (coal and nuclear), diesel plant and gas thermal plant. When the wind power is introduced, this may change the production levels of thermal power plants. Any restrictions and possibilities concerning their flexibility should be taken into account when making the study.

T1 Consider the ramp rates of the thermal power plants.

T2 Consider the start/stop costs and time lags of the thermal power plants.

T3 Consider the varying efficiency depending on the operation point.

T4 Consider the coupling between the power and heat production in CHP units.

The best method is to use all these models at the same time, i.e. T1 + T2 + T3 + T4. This is possible if the region simulated and time resolution (Section 11) is not too short. But to do this in combination with the consideration of uncertainties (Section 7) and shorter timer resolutions (shorter than hours) is a big challenge.

10 Modelling of wind power – (W – Wind)

Studying system impacts from wind power often means studying an increased amount of wind power (compared to the current situation) in a large geographical area and usually wind farms are distributed over a wide area. This brings significant smoothing effect on variations of the production and also reduces the forecast errors. Upscaling data from very few existing wind farm sites will upscale the variations and not take into account the smoothing effect, which is especially strong for hourly and less than hourly time scales. The variations and forecast errors of wind power are the issues causing integration costs (Nørgård et al., 2004). Wind power input is therefore crucial for integration study results. The size of the area as well as the foreseeable distribution of wind power should be taken into account when estimating the range of smoothing effects. Usually, the possibilities for future wind scenario data is either to use simulated data or data based on upscaled realised production. Wind power production data have been easier to get for monthly or yearly time scales, whereas data for hourly or especially less than hourly have not been easily available for most countries.

W1 Use wind speed measurements from few places and convert to power using power curve of a wind turbine. This assumes single turbines, neglects smoothing in wind farms (considerable in time scales of one hour and less) and assumes wind power concentrated in few places.

W2 Use wind farm power production data from tens of sites. To capture the smoothing effect of any size of area correctly, 20–50 sites from different parts of the area should be used (Focken et al., 2001).

W3 Use W1 or W2 in combination with smoothing techniques to arrive at the variability that corresponds to future wind power distribution and size of area simulated (Holttinen, 2004).

W4 Allow for large wind farms (e.g. offshore) to be controllable by central grid dispatch, e.g. as a form of spinning reserve.

W1 is not correct and will overestimate the consequences of wind power to the power system. The best method is to use the data for aggregated wind power taking into account appropriate smoothing effect and the data for wind power forecast errors – W2 with enough data or W3. Forecast errors of wind power are also relevant in modelling the wind power, discussed in uncertainty (Section 7).

11 Simulation of system operation – (S – Simulation)

There are several ways to simulate the operation of the power system, with or without wind power.

S1 Simulate one possible situation, e.g. one representative year with and without wind power in a deterministic way, i.e. all the load levels are known in advance. This approach is used in Holttinen and Pedersen (2003).

S2 Simulate several possible situations, e.g. apply a Monte Carlo technique to possible wind scenarios, thermal power plant availability and/or load behaviour. Apply deterministic optimisation for each scenario.

S3 Simulate several possible situations, e.g. apply a Monte Carlo technique to possible wind scenarios, thermal power plant availability and/or load behaviour. Apply stochastic optimisation for each scenario, i.e. assume that the operation of the system is replanned continuously when new forecasts are available. The Wilmar project (Weber et al., 2004; Wilmar, 2005) uses this approach for wind power.

Here S3 represents the best method since it reflects how the system is operated in reality where the different actors continuously consider the new information about the system state and forecasts and based on this they take decisions about how to operate the different controllable devices in the system. But to really simulate this for a system consisting of several countries, with uncertainties for both wind power and load and other production and transmission and where the decisions are taken every minute, is not possible (at least not currently).

12 Time resolution – (R – Resolution)

There is always a trade-off between the size of the time step and the run time of the simulation model. A shorter time step is often more accurate, but requires much more data and longer simulation times. A general division is:

R1 Use daily or weekly resolution, i.e. the only possible result is then MWh per week or MWh per day. This is used for some main modelling in (Holttinen, 2001). With this time resolution, it is possible to run several years, reflecting, for example, the uncertainty of hydropower resources.

R2 Use hourly resolution, i.e. results are possible concerning for example hourly mean peak values measured in MWh per hour. With this resolution, it is possible to run a whole year for a single country (Pedersen, 1990; Lund and Münster, 2003), but for regional power systems with several countries this is already a heavy task (Wilmar, 2005).

R3 Use shorter resolution, e.g. minutes, seconds or even shorter. It is then possible to study, e.g. unforecasted wind speed variations and their balancing within the hour, consequences of outages in power plants, power flow problems in grids. This time resolution is needed to study, for example, possible blackout situations. This approach is needed for the method G5.

The shorter the time resolution, the more accurate should be the results. This is of course assuming that the same calculations are made with two time resolutions. Since computer takes much time for R3, this method is often used for single situations or single hours, while method R2 can simulate more situations. As computing power increases, however, so does the ability to accommodate shorter time resolution in models. It is therefore a challenge to get the correct model in R2 that reflects the limitations that need to be simulated with R3. Resolution R1 will only give general results on what fuels are replaced by wind power production. Nearly all system impacts of wind power require modelling in hourly time scale, to catch the variability and forecast errors of the wind power.

13 Pricing method – (P – Power)

When a certain power system is operated, all involved actors consider the costs of their own resources and the prices on the market. When the operation of a future power system is simulated, this means in reality that one has to do some estimation about how the different actors will behave on this market. When the term ‘integration cost’ is used, it is of course essential to know whether this is a cost for the society or if it is only a transfer of money from one actor to another one. If we get a significant ‘integration cost’ of wind power, but this depends on a dominating market position among the power companies that have the regulating power resources, then the ‘integration cost’ to a large part consists of an increased profit for these companies, i.e. it is not a ‘cost’ for the whole society.

P1 Use the costs such as fuel and investment costs for both the studied system and neighbouring systems. Of course, also these 'costs' are based on the market prices, but at least the input costs for all involved companies can be considered.

P2 Use the prices for trading with neighbouring systems, for example. The consequence of this may be that what is a 'cost' in the studied system, may be a profit in the neighbouring systems. A challenge with this approach is to estimate how the pricing of the trading with the neighbouring systems will change in a future system.

P3 Use a simulation method where all the companies and system operators, are treated individually where each actor maximises its benefit (according to some definition), considering the physical and legal constraints.

P4 In addition to P3, the dynamics of the market can be included in such a way that the different actors on the market make investments or change their behaviour depending on the market prices. This will then change the prices on the market. This approach is about the same as M3.

The best method is P4 since it corresponds to how the real system is run. With a correct model (which of course is a big challenge), this means that it will be possible to estimate not only the 'integration cost' but also the changes in different prices. But this method is based on the assumption that costs and possibilities to reduce them are available for all actors in the system and this is normally not the case.

14 System design method – (D – Design)

There are two items that have to be designed in the system: the physical system and the market rules. Referring to Figure 2, the question is about these design issues for the replaced system and for the system with the new source. Are they the same? For large amounts of wind power, it is important from the integration cost point of view that the design of system 1 and 2 are optimal, both from the physical design point of view and from the market rules point of view. With a large amount of wind power, the possibilities of trading reserve power is essential and if the main trading of power is on a daily market, then wind power will have some problems since the quality of day ahead (12–36 hour) forecasts is comparatively low. Day ahead forecasts are normally not needed from the technical point of view, since most start-up times for thermal power plants are in the range of some hours. So the question is then how this is considered in the study:

D1 Use the same physical remaining system for both the replaced system alternative and the system with the new source, i.e. assume the same transmission lines and power plants for both remaining systems. Also assume exactly the same market rules for both systems. This corresponds to M1.

D2 Assume that the remaining production system is optimised. For wind power it may be optimal from the economical point of view that the remaining system consists of plants which are relatively easy to control up and down. The general idea is to minimise the total cost (operating + investments) for the system with a larger share of wind power. This approach is included in P4 and M3.

D3 Assume that the number of transmission lines is optimised. When adding wind power to a future system it may be optimal from the economical point of view to add more transmission lines to the regions with better possibilities of balancing the wind power. It is, on the other hand, probably not optimal to always be able to transmit maximum possible wind power production in a situation with minimum load in the same region as the wind power, if the probability for this is very low. The general idea is to minimise the total cost (operating + investments) for the system with a larger share of wind power. This approach is also included in P4 and M3.

D4 Assume perfect trading rules, i.e. if the different actors on the market try to maximise their objectives according to the market rules, then the total surplus in maximised. It can generally be stated that this is a big challenge both for the reference alternative and for the alternative with the new source.

The most correct method of simulation of a future system is to use D2 + D3 + D4, which means an assumption that the actors on the market adapt themselves to the new situation. The biggest challenge here is to consider D4, since it is not always so easy to get the correct market rules. This statement is based on the assumption that the strong actors on the power market (the power producers) do not have an interest to change the rules to obtain a better competition if they do not make a benefit on the change of rules.

15 Comments and conclusion

In this paper, the impact of some modelling issues on the estimation of the ‘integration cost’ of wind power has been discussed. The aim of such a study should be to estimate the difference in cost between a reference system and a system with the new source (excluding the investment and operation costs of the new source). The best method should therefore simulate the design and operation of these two alternatives as much as possible.

The different cases and input data to be considered are summarised in Table 1. The ideal method should be to:

1. Estimate how an economically efficient system should be configured if the amount of wind power increases with a certain amount per year = M3.
2. Consider all imbalances in the system = I3 and all balancing possibilities, i.e. also the ones outside the region where the wind power source is located = B3.
3. Perform full-scale dynamic analysis of the power system for all the relevant operation and fault situations = G5.
4. Consider all uncertainties in the system: stochastic optimisation concerning the seasonal planning of hydropower systems, transmission limit uncertainty, load uncertainty and thermal plant uncertainties. Also assume that best available forecasts are available for each region with wind power plants = U1 + U2 + U5 + U6 + U7.
5. Consider head height depending power production for the hydropower plants, hydrologic coupling between hydropower plants in the same river and hydrological/flow restrictions = H1 + H2 + H3 + H4.

6 Consider ramp rates and start/stop costs of thermal power plants, varying power plant efficiency depending on operation point and coupling between power and heat production in CHP units = T1 + T2 + T3 + T4.

7 Take wind input time series that are aggregated to produce a correct amount of smoothing effect for the region size relevant to the study = W3. W4 should also be included when there are wind farms having the option to provide ancillary services.

8 Simulate several possible situations, e.g. apply a Monte Carlo technique to possible wind scenarios, thermal power plant availability and/or load behaviour. Then apply stochastic optimisation for each scenario = S3.

9 Use a short time resolution, e.g. minutes or seconds to consider all possible situations in the system = R3.

10 Use a simulation method where all companies and system operators, are treated individually and each actor maximises its benefit (according to some definition – i.e. their utility function) considering the physical and legal constraints. Also include the dynamics of the market in such a way that the different actors on the market make investments or change their behaviour depending on the market prices = P4. If a technical integration cost and not market-based integration cost is sought for, then also P1 + P2 could be sufficient.

11 Assume that all parts of the system are optimised, the amounts of transmission lines, number of power plants and type of power plants, as well as market rules = D2 + D3 + D4.

In reality, it is impossible to have one method that contains all these points 1–11. This means that all integration studies where an ‘integration cost’ is to be estimated will be based on approximate studies, usually divided on different time scale studies for different aspects of power system operation. The level of detail chosen for these would then have to take into account the power system characteristics, wind power penetration and distribution on the area, wind power technology options to provide for reserves, fuel price developments and CO_2 reduction value, etc.

In order to get a qualitative judgement of the estimated ‘integration cost’, it is necessary to have some kind of knowledge about the impact of performed approximations. The main aim of this paper is mainly to structure the methods in order to make it easier to see what kind of approximations that have been used. It is not a problem to make approximations as long as there is some knowledge about the impact from these approximations on the final result.

It can be noted that it is not a trivial task to estimate the consequence of an approximation without comparing two results: one with the approximation and one without. But at least one has to start with a description of what kind of approximations that have been used.

It can also be noted that it is not a trivial task to classify the existing integration reports according to Sections 2–11, since it is not so common to write exactly which methods and approximations that have been applied in the study.

Table 1 Modelling the integration costs of wind power. Methodology and input data to be considered

Item		*1*	*2*	*3*	*4*	*5*
A	Aim of study	What happens with X GWh wind	How much wind is possible			
M	Method to perform study	Add wind energy	Wind also replaces capacity	Optimal system design		
I	Imbalance calculation	Only wind	Wind + load	Wind + load + production		
B	Balancing location	Dedicated source	From the same region	Also outside region		
G	Grid limit on transmission	No limits	Constant MW limits	Consider voltage	N-1 criteria	Dynamic simulation
U	Uncertainty treatment	Transmission margins	Hydro inflow uncertainty	Wind forecasts: U3: no U4: persistance U5: best possible	U6: load forecasts considered	U7: thermal power outages considered
H	Hydropower modeling	Head height considered	Hydrological coupling included	Hydrological restrictions included	Availability of water considered	
T	Thermal power modeling	Ramp rates considered	Start/stop costs considered	Efficiency variation considered	Heat production considered	
W	Wind power modeling	Few wind speed time series	Many wind power time series	time series smoothing considered	Allow controllable wind power	
S	Simulation model of operation	Deterministic simulation, one case	Deterministic simulation several cases	Stochastic simulation several cases		
R	Resolution of time	Day/week	hour	Minute/sec		
P	Pricing method	Costs of fuels, etc.	Prices for trading with neighbours	Market actor simulation	Market dynamics included	
D	Design of remaining system	Constant remaining system	Optimised remaining production	Optimised remaining transmission	Perfect trading rules	

Acknowledgement

This work has been made in the international collaboration IEA WIND Task 24 Integration of Wind and Hydro power systems http://www.ieawind.org".

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