# IMPACT OF HOURLY WIND POWER VARIATIONS ON THE SYSTEM OPERATION IN THE NORDIC COUNTRIES

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**Abstract:** The Nordic power system data is used to estimate the impacts of wind power variations to the hourly variations seen by the system. The incremental increase is derived by looking at the hourly variations of load and wind power. The result of the Nordic time series is that there will be an increasing impact with increasing wind power penetration. Taking into account better predictability of load, the increase in reserve requirement becomes 1.5–4 % of wind power capacity at wind power penetration level of 10 % of gross demand. The increased reserve cost is of the order of 1 €/MWh at 10 % penetration and 2 €/MWh at 20 % penetration. The reserve cost is halved if the investment costs for new reserve capacity are omitted and only the increased use of reserves is taken into account. In addition, prediction errors in wind power day ahead will appear in the regulating power market to an extent which depends on how much they affect the system net balance and how much the balance responsible players will correct the deviations before the actual operating hour.

**Keywords:** wind power, power system impacts

## 1. INTRODUCTION – SYSTEM IMPACTS OF WIND POWER

The drawbacks of wind power, from the power system point of view, are its variability and unpredictability. However, these problems are greatly reduced when wind power is connected to larger power systems, which can take advantage of the natural diversity in variable sources. Large geographical spreading of wind power will reduce variability, increase predictability and decrease the occasions with near zero or peak output.

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. Even though the wind power penetration in some island systems (e.g. Crete in Greece) or countries (e.g. Denmark) is already high, on average wind power generation represents only 1–2 % of the total power generation in the Scandinavian power system (Nordel) or the Central European system (UCTE). The penetration levels in the USA (regional systems) are even lower.

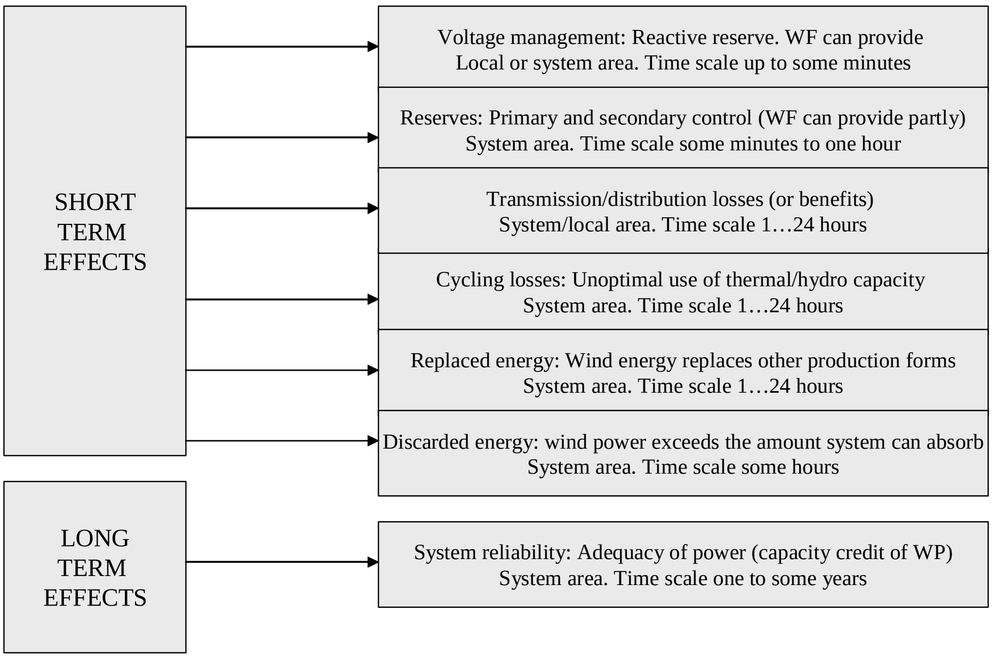


*Figure 1. System impacts of wind power (WP) and wind farms (WF), causing integration costs. Part of the impacts can be beneficial for the system, and wind power can have a value, not only costs.*

The need for more flexibility to meet larger fluctuations in the system depends on the portion of consumption covered by wind power production. Also, power systems are different in how much inherent variability in the system (the load) there is and in how loaded and well meshed the system is (available transmission). The amount of flexibility already there in the system, as well as the amount that can be cost effectively increased is important. The treatment of imbalances in the power systems differs internationally.

The system impacts of wind energy are presented schematically in Figure 1. These impacts are divided into two parts: short term, balancing the system during the operational time scale (minutes to hours), and long term, providing enough power and energy in peak load situations.

*Voltage management* is a more local issue, where measures should be taken when wind farms are installed. Modern wind farms can be equipped with power electronics providing voltage management, reactive reserve and some primary control [1].

Wind power can either decrease or increase the *transmission and distribution losses* depending on where it is situated in relation to the load [2]. First experiences from West Denmark and the northern coast of Germany have shown that when significant amounts of electrical demand are covered with wind power, it is first seen as increased transmission with neighbouring countries or areas [3;4].

*Discarded energy* occurs only at substantial penetration and it depends strongly on the operational strategy of the power system. At a wind power penetration of about 20 % of the gross demand, wind power production may equal the demand during some hours (a 100 % instant penetration). When wind power production exceeds the amount that can be safely absorbed while maintaining adequate reserve and dynamic control of the system, a part of the wind energy produced may have to be curtailed. In West Denmark, few occasions of curtailment have occurred since the year 2001 when wind power exceeded 16 % penetration on a yearly basis.

The results from estimating the *increased reserve requirements* show a very small impact on primary reserve (regulation time scale) [5;6;7;8]. For secondary reserve (load following time scale), there is an increasing impact with increasing penetration [2;9;10]. The first estimates regarding the increase in secondary (load following) reserves in the UK and US thermal systems suggest 2–3 €/MWh for a penetration of 10 % and 3–4 €/MWh for higher penetration levels (2;6;11)[1]. It is difficult to compare the results from the studies made so far. The different results for the cost estimates are due to different system characteristics, penetration levels and study methods. The studies made so far often use simulated wind power output data that exaggerates the variations in wind power production, and make conservative assumptions unfavourable to wind power. A caveat in some of the studies is a modelling approach not taking into account the flexibility in the system, such as hydro power [12].

In the time scale of unit commitment (4…24 h), wind power can cause extra costs for the system, if the operation of the power plants is made more inefficient due to varying wind power production and prediction errors. The positive effects of wind power, reduced fuel use and emissions are also issues relevant in this time scale. Day-ahead predictions are required in order to schedule conventional units [13].

Power system studies are often carried out considering the system as it was operating before the liberalisation of electricity markets. Balancing the forecast errors between the bids and the delivery is the responsibility of the power producer. Theoretical studies on how wind power would come to the markets have shown that market design has a crucial effect on wind power producers in how the regulating costs are allocated [14;15]. In West Denmark, with a wind penetration of about 20 %, it is the responsibility of the transmission system operator (TSO) to balance the so-called prioritised production. The cost for compensating forecast errors in the day-ahead market at the regulating market has amounted to almost 3 €/MWh [3].

*The long term effects* concerning the adequacy of supply involve the estimation of capacity value for wind power. The ability of wind power to offset conventional capacity, capacity credit, has been widely studied. The results of several studies of wind power capacity credit [16] show that at low wind power penetration the capacity credit is close to the average production of wind power during times of high loads. When wind power penetration is increased, the capacity credit will decrease.

## 2. WIND POWER DATA, SMOOTHING AND REPRESENTATIVITY

The data used in this study is the measured output of wind power plants and wind parks. Realised hourly wind power production time series from Denmark, Finland, Sweden and Norway were collected. Data was collected for three

[1] Currency exchange rate from the end of 2003 used: 1 € = 1.263 $ ; 1 € = 0.705 £

years 2000 to 2002. Special care has been taken to get representative data for wind power production synchronous with load data from the 4 Nordic countries.

Before up-scaling the wind power production data, the proper smoothing effect has to be present in the data. When enough turbines from a large enough area are combined, the smoothing effect reaches saturation, and the time series can be up-scaled with representative hourly variations. The statistical properties of large scale wind power were studied to find out the properties of a representative large-scale wind power production data set in previous paper [17;18].

## 3. OPERATING RESERVE REQUIREMENTES FOR WIND POWER

Dimensioning of the disturbance reserve in each Nordic country is based on the largest production unit tripping off instantaneously. In addition to this secondary reserve, operational reserve is also needed. In Nordel power system, this is taken from the regulating power market. Wind power has no influence on the disturbance reserve when wind farms are less than 1200 MW in size.

The additional requirements and costs of balancing the system on the operational time scale (from several minutes to several hours) are primarily due to the fluctuations in power output generated from wind. To estimate the impact of wind power on power system operating reserves, it has to be studied on a control area basis. Every change in wind output does not need to be matched one-for-one by a change in another generating unit moving in the opposite direction. It is the total system aggregation, from all production units and consumption with its uncertainty, that has to be balanced.

### Primary reserve

Primary control is performed on a time scale of seconds/minutes. On this time scale, there is no correlation between the variations of geographically dispersed wind farms [5].

A rough estimate of the order of magnitude that large-scale wind power has on the primary reserve requirement assumes that increase in wind power and its variations requires the same addition to reserves as the increase in electricity demand and its variations [19]. The primary reserve has been 600 MW for 360 TWh/a demand in the synchronously operated Nordic area [20]. Assuming an increase relative to how much variable consumption there is, producing 10 % of the demand with wind power (36 TWh/a; 18 GW wind power) would increase the primary reserve by 10 %. This means an increase of 60 MW or about 0.3 % of the wind power capacity installed.

### Secondary reserve

For operational reserves, the unforeseen variations induced from wind power are relevant on the time scale of 10 min...1 hour. To estimate the impact of wind power on the secondary reserve, wind power variations are studied combined with the load variations: the net load is the load minus the wind power production for each hour.

Planning and operating a power system is based on probabilities and risk. Reserves in the power system are determined so that variations within a certain probability are covered, for example 99.99 % of the variations. Standard deviation $\sigma$ indicates the variability of the hourly time series: for a normally distributed probability distribution a range of $\pm 3\sigma$ will cover 99 % and $\pm 4\sigma$ will cover 99.99 % of all variations. In this work, $4\sigma$ is used as a confidence level to determine the amount of reserves that need to be allocated in the power system. The increase in the variations due to wind power is $4(\sigma_{NL} - \sigma_L)$, where $\sigma_{NL}$ is the standard deviation for the net load and $\sigma_L$ for the load, respectively.

Calculating the increase in variability this way assumes that wind power only contributes to the reserve requirement by the increase due to its addition to the system. This means that wind power can make use of the benefits of the existing power system.

To account for the better predictability of load [10], a case study for Finland was performed for year 2001 load data with load forecasts. The standard deviation of the forecast error was 123 MW (1 % of peak load), in comparison with 268 MW for the load hourly variations. This indicates that about half of the variability in load can be predicted. Comparing the load forecast error with wind power variations resulted in a 100 % increase in net load variations.

The results are summarised in Table 1 and Figure *2*. As Denmark consists in practice of two separate areas, the West Denmark results are also of interest. They are roughly the same as the results presented here for Denmark.

The estimation is based on hourly wind power data from a 3-year-period in which the wind resource was less than average. This may underestimate the true variations. For the Danish data, the error was estimated to be of the order of 5 %, and it has been added to the results in Figure *2* and in the last section of Table 1.

The results show that when the penetration of wind power in the system increases, an increasing amount needs to be allocated for operating reserve. When the Nordic system works without bottlenecks of transmission the impact of wind power becomes significant at 10 % penetration level, when the increase in reserve requirement due to wind power is about 2 % of installed wind power capacity or 310–420 MW. At a high wind power penetration of 20 %, the increase is already about 4 % of wind power capacity or 1200–1600 MW.

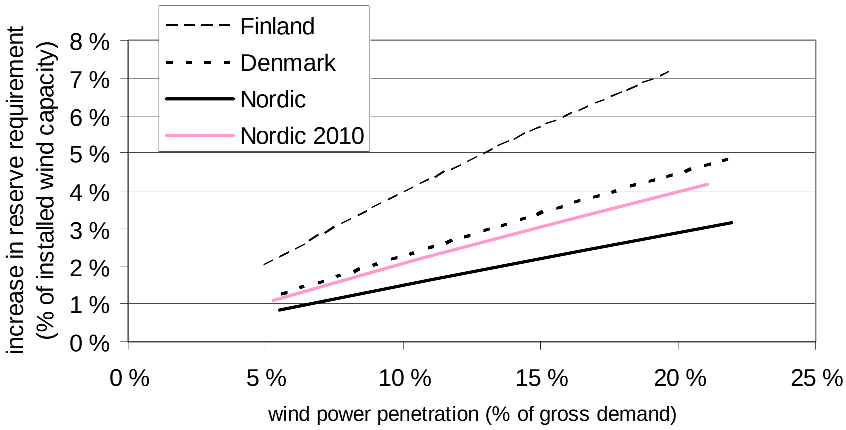


*Figure 2. Increase in hourly load following requirement for wind power, calculated from the standard deviation values of load and wind power production from years 2000–2002. Increase is relative to installed wind power capacity.*

*Table 1.The increase in reserve requirement due to wind power with different penetration levels. Statistical analysis of hourly data for wind power and load in the Nordic countries for 2000–2002.The range in Nordic figures assumes that the installed wind power capacity is more or less concentrated.*

| | Finland | | Denmark | | Nordic | |
|---|---|---|---|---|---|---|
| | MW | % of peak load or capacity | MW | % of peak load or capacity | MW | % of peak load or capacity |
| Range of hourly variations*: | | | | | | |
| - Load | -985–1144 | -7.2–8.4 | -862–1141 | -13.7–18.1 | -5138–6698 | -7.6 –9.9 |
| - Wind | | -15.7–16.2 | | -23.1–20.1 | | -10.7–11.7 |
| Stdev of hourly variations: | | | | | | |
| - Load | 268 | 2.0 % | 273 | 4.3 % | 1438 | 2.1 % |
| - Wind | | 2.6 % | | 2.9 % | | 1.8 % |
| Increase in variations (4□2000-2002 data: | | | | | | |
| - 5 % penetration | 20 | 1.0 % | 6 | 0.6 % | 40-55 | 0.4-0.6 % |
| - 10 % penetration | 80 | 2.0 % | 24 | 1.2 % | 155-210 | 0.8-1.1 % |
| - 20 % penetration | 285 | 3.6 % | 94 | 2.4 % | 600-800 | 1.6-2.1 % |
| Increase in reserve requirements: | | | | | | |
| - 5 % penetration | 40 | 2.0 % | 13 | 1.3 % | 80-110 | 0.8-1.2 % |
| - 10 % penetration | 160 | 3.9 % | 50 | 2.5 % | 310-420 | 1.6-2.2 % |
| - 20 % penetration | 570 | 7.2 % | 200 | 4.9 % | 1200-1400 | 3.1-4.2 % |

*The hourly load variations are 99 % of the time between -7.2…16 % of peak load in Denmark, -4.4…6.6 % of peak load in Finland and -4.4…7.4 % of peak load in the total Nordic time series. The hourly variations of large scale wind power production are 99 % of the time between ± 10 % of installed capacity for Finland and Denmark and about 98 % of the time between ± 5 % of installed capacity for the total Nordic time series.

The prediction errors of wind power 2...24 hours ahead may also require extra balancing at the regulating power market. The increased balancing requirements would be seen either as changes of schedules at the balance responsible players responsible for wind power production, or or as individual imbalances that might affect the system net imbalance.

## 4. COST OF INCREASE IN RESERVE REQUIREMENT

Both the allocation and the actual use of reserves cause extra costs. The same reserve capacity can in principle be used for both up and down regulation. Either up or down variations can determine the need for increase in the reserves. In most cases, the increase in reserve requirements at a low wind power penetration could be handled by the existing capacity. This means that only the increased use of dedicated reserves or increased part-load plant requirement will cause extra costs. Beyond a threshold, the capacity cost of reserves also has to be included. In the Nordic countries this threshold depends on whether there is still capacity available to bid to regulating power market.

Regulation power almost always costs more than the bulk power available on the market. The reason is that it is used during short intervals only and that it has to be kept on stand-by. The cost of reserves depends on the type of production. Hydro power is the cheapest option and gas turbines are a more expensive one.

The cost of increased reserve in the hydro power system is difficult to obtain. Thus, the cost is estimated in two ways: based on thermal capacity costs and on existing regulating power market prices.

### Primary reserve

The cost of an extra 60 MW in the Nordic synchronous area, for 36 TWh/a wind power production producing 10 % of the gross demand, is the price for reimbursing the power plants for using automatic frequency control. This is paid irrespective of the use, for all the hours the reserve is allocated. Using the prices from Finland (3.3 €/MWh + fixed 7500 € per MW, Fingrid, 2004), the primary reserve cost for 10 % wind power penetration would be less than 0.1 €/MWh of wind power produced. An increase of 60 MW in reserve requirement is conservative, as the total 600 MW has been in use in the Nordic countries for years, irrespective of the load increase.

### Secondary reserve

The estimate for the increase in reserve requirement due to wind power in the case of the Nordic countries, is 310–420 MW at a 10 % wind power penetration and 1200–1400 MW at 20 % penetration (Table 1), depending on how concentrated the installed capacity will be. The corresponding costs can be estimated by increasing flexible natural gas combined cycle (NGCC) gas turbines in the power system (investment cost 505 €/kW). Dividing the annualised costs of NGCC (a=13 %) to the wind power production results in a cost of 0.5…0.7 €/MWh at 10 % penetration and 1.0…1.3 €/MWh at 20 % penetration level.

The relevant reserve cost for wind power is determined by the Nordic regulating power market. The extra paid for regulation is the difference between the spot price and the regulating market price. This has been on average 4–5 €/MWh for up regulation and 5–9 €/MWh for down regulation in Finland, and 6–8 €/MWh up and 10–15 €/MWh down in West Denmark in 2001–2003. The increased cost of thermal capacity for operating at secondary reserve has been assumed as 8 €/MWh [9], so the market prices are in line with the actual costs. Assuming a price range of 5…15 €/MWh for the extra reserve used, the cost of increase regulation need in Finland is 0.2...0.5 €/MWh wind power produced at a 10 % wind penetration level and 0.3…0.8 €/MWh at 20 % penetration For the Nordic dataset, the cost is 0.1…0.2 €/MWh for 10 % penetration and 0.2…0.5 €/MWh for 20 % penetration, respectively [21].

Since the opening of a common regulating power market, most of the reserve power activated has been from Norway and Sweden, with the lowest bids from the large regulated hydro plants. There seems to be ample capacity bidding to the regulating power market [22]. It is thus unlikely that an increase in wind power would result in new reserve capacity being built. However, it is quite likely that a major increase in wind power would result in an increase in the regulating market price. In a situation where the cheapest reserves have already been used and more expensive new reserves have to be allocated, the costs of regulation may rise substantially and suddenly. This is why the historical prices can be used to estimate the costs only as long as the reserve amounts needed are such that the regulating capacity bidding to the market has a similar price. In West Denmark with 16...20 % wind power penetration, the down regulation costs have increased 50 % but no other changes have been observed. With the cost range presented here, the higher estimate of 15 €/MWh accounts for doubled regulation market prices due to wind power.

## 5. SUMMARY AND CONCLUSIONS

When the Nordic system works without bottlenecks of transmission wind power will increase the reserve requirement for about 2 % of installed wind power capacity or 310–420 MW. At a high wind power penetration of 20 %, the increase is already about 4 % of wind power capacity or 1200–1600 MW.

The cost of increased operating reserves in the Nordic power system will be nearly 1 €/MWh for a 10 % penetration and nearly 2 €/MWh for a 20 % penetration. These costs would be halved if the conservative estimate for allocating investment costs for new reserve capacity to the wind power production is replaced by the increased use of reserves only.

These estimates present a theoretical approach for estimating the order of magnitude of the effects of wind power variability on the system operation. The variations in wind power production are probably still somewhat conservative for the total Nordic area, as the smoothing effect of thousands of wind turbines at hundreds of wind farm sites is underestimated by the data sets used. It has been assumed that the hourly variations give an estimate of the secondary reserve operated on a 10–15 minutes scale. As the wind power varies less within an hour than on an hourly basis, using hourly data would not underestimate the effects.

The cost estimates derived here are less than in most studies before [2;6;11]. This is due to a large area (Nordic system with 4 countries) and thus a smoothed output of large scale wind power production.

The prediction errors of wind power 2...24 hours ahead may also require extra balancing at the regulating power market. The increased balancing requirements would be seen either as changes of schedules at the balance responsible players responsible for wind power production, or as individual imbalances that might affect the system net imbalance.

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