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Impact of wind power on the power system imbalances in Finland

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Abstract— *This paper presents a study on the imbalance costs or payments that wind power producers pay on the one hand and the cost incurred for the power system on the other hand. Both the producer side and the system side will be examined with case data on prediction errors, system net imbalances and the balancing costs. The up-scaled forecast errors of wind power that result in imbalances have been combined with the system real net imbalance. There is comparisons and discussion about the balancing costs of wind power depending on the wind penetration. The results for case Finland show that a two-price system for imbalances results in higher imbalance costs than a one-price system. At low wind power penetration levels, the difference in imbalance payments is high for one- and two-price system. When wind penetration increases, there is not so much difference in the different balance settlement rules used. According to comparison between imbalance payments and system costs, the increase in system costs due to wind power is lower than imbalance payments for wind power producers when using either average prices for up- and down-regulation or the regulation prices which increase linearly with regulation demand.*

Index Terms—Forecasting, wind energy, electricity markets, balancing costs, balance settlement.

1 Introduction

Wind power production is variable but can be forecasted to some extent. In the Nordic electricity market, as in several other day-ahead markets, bids can be submitted at noon previous day for all hours of the next day. This means forecasting wind power production 12-36 hours ahead, or 14-38 hours ahead to account for time for trading. In balance settlement, the imbalances due to prediction errors will be charged from producers.

The imbalance costs for wind power can be substantially high due to errors in forecasting hour-by-hour the production day-ahead. It is common that imbalance costs contain a penalty. This has a directive action, puts an incentive to producers to keep their schedules and thus reduce the balancing effort that the system operator has to make real-time. However, as wind power producers have very limited possibilities to improve the predictions; no matter how high penalties are set there will still be imbalances from wind power. Ideally, the balance settlement rules should be such that imbalance payments would reflect the true costs that wind power incurs to the power system.

In Finland, Sweden and Norway there is no feed-in tariff for wind power. The wind power producers have to make contracts selling their electricity or trading it in markets and also make contracts for balance settlement. Today, based on the rules of Nordpool electricity exchange, the wind power producers need to give a production estimate for the next day (12–36 hours ahead). In practice all wind power producers have contracts with Balance Responsible Players. Balance Responsible Players take all the estimates for production and consumption and put them together. After balance settlement is done, wind power will bear

its share of the balancing costs induced from the forecast errors for each hour.

This paper relies on data from previous work where it has been shown that in Finland the day-ahead forecast horizon results in forecast errors that correspond 30 to 40 % of the yearly energy production, depending on how distributed the wind farms are [1]. There exists also other previous work outlining the balancing costs of wind power in different markets. This has been done to show the value of forecasting service to wind power producers [2,3,4,5,6]. There have also been publications on the impact of wind power forecast errors to the system operation [7]. Experience from countries with considerable wind power penetration (Denmark, Germany, Spain) show that adding wind will increase demand of balancing [8,9]. In Sweden the case of balance responsible actors trying to minimize their balance costs from different wind power portfolios (distributed/single power plant) in the Nordic electricity markets was studied in [10]. Also, the option of using an intra-day market was studied to correct the day-ahead forecasts as better forecasts come available. The influence of wind power to the local energy system and prices in the West Denmark (Jutland/Funen) has been analysed in [11]. There, no strong correlation between local wind generation and spot prices was observed, while a correlation between generated wind power volume and up and down regulation volume was established. There are several previous publications on wind integration impacts on reserve requirements and technical balancing cost increase. A summary of this work and results can be assessed in for example [8,12]. According to [8] the integration cost for wind power resulting from balancing the extra variability and forecast errors of wind power in the power system adds about 1-4 €/MWh for wind power produced, at penetration levels of 10 % of gross demand and below.

This paper adds to the previous work firstly by showing the result of using different imbalance payment rules to the balancing price paid by wind power producers, but also by comparing with same data the costs paid by the producers and the increase in costs for the system operator. As the imbalances due to wind and load forecast errors do not correlate, wind power will not impact the overall total imbalance at small wind power penetrations. The impact of wind prediction errors might be seen during some individual hours, sometimes adding to the net imbalance, sometimes reducing the net imbalance. The question is at what penetration level of wind power the forecast errors start to impact on the system net imbalance, incurring more costs.

Section 2 is an introduction on the Nordic market, imbalance prices and their link to balancing market. Section 3 describes the data used in the analyses. Section 4 shows the balancing costs for wind power producer operating in the markets. Two options are analysed: (a) two-price system (b) one-price system. Section 5 estimates the costs that imbalances incur for the system operator (case Finland). Section 6 compares the two costs for different wind penetration levels for one- and two-price systems and Section 7 summarises the results.

2 Regulating power market price, imbalance price and one/two price system for balance settlement

In the Nordic electricity market there is a link between the imbalance prices used in balance settlement and the total regulating power used for balancing the Nordic power system. The Nordic power system is operated as one large system, where both the day-

ahead market (Elsport), the intra-day market (Elbas) and the balancing market (Regulating Power Market) are common for the four countries. In case of bottlenecks of transmission, there will be different price areas. System is balanced first by instantaneous primary reserve activated automatically and then the TSOs call manually to activate bids from the balancing market, called regulating power market, to correct for frequency deviations. The TSOs use the regulating power (activated in 10 minutes) from the regulating power market to balance the total net imbalance of the Nordic power system. The last bid that is used from the balancing market determines the price paid for regulation for that hour. This same price is used for balance settlement.

Imbalance settlement is made first for all balance responsible parties in the market, and they usually make the imbalance settlement forward to all individual actors in the market. In practice, all producers and consumers will have imbalances, but most of these will counterbalance each other. This will result in more imbalances being charged than what the TSOs pay for regulating power (Fig 1). There are also differences in how the producers are treated during hours when their imbalance is reducing the net imbalance of the system (one- or two-price system). Fig 1 illustrates the counterbalancing: several individual imbalances (either to opposite side or to same side with the system net imbalance) are summed up forming the system net imbalance.

Fig 1. System net imbalance is considerably lower than the sum of individual imbalances from all the actors, because a lot of the imbalances will be counterbalanced (to opposite sides) in a large power system. The sum of individual imbalances that are increasing the system net imbalance (above on the right side) is what is charged by TSOs for imbalances. This is more than the system net imbalance that the TSOs are paying regulating power market price for.

In Finland, Sweden and Denmark a two-price system is in use. Only those imbalances of individual players that are contributing to increase the system net imbalance will have a regulation price differing from the SPOT market price (Fig 1 Producers 7, 8, 9,...). Other imbalances are dealt with according to SPOT-price and this means that the actual production during these hours will be paid for according to the SPOT- price. For all imbalances, however, a fixed volume price is used (0.7 €/MWh in Finland). In Norway, one-price system is used, where the TSO circulates the money it gets from the imbalances that increase the system net imbalance to the producers whose imbalances reduce the system net imbalance (Fig 1 Producers 1, 2, 3...).

A day-ahead market as the SPOT Nordic market is tough for wind power producers and results in large balance errors. If a one-price system were used for balance settlement, like in Norway, the balance costs would be near 0 as long as wind power does not affect the overall demand in the regulating power market [2].

Nordel has investigated means to harmonise the balance settlement rules now used in different countries and has proposed to use one-price system for consumption and two-price system for production imbalances in future [13].

3 Data

Wind power production prediction error data is for Finland from year 2004. Wind forecasts (Foreca model ETA) were made for altogether 12 sites along the West coast of Finland, at most 600 km apart. A time series model for wind power prediction was made for the 12 sites. Wind power prediction uses as input the on-line data of the wind farm as well as wind speed and direction forecast 3 hours ahead. The parameters for ARX type time series modeling are estimated aligning wind forecasts with existing data for the wind farm production, minimizing the error. Models and data are described in more detail in [1, 14], where there are also comparisons for the forecast errors and imbalance costs for different aggregations of wind power along the coast of Finland. In the previous study two time series were calculated: day-ahead (12 - 36 h) prediction error time series with Normalised Mean Absolute Error NMAE 7.7 % of installed capacity and 3 hours (3 h) ahead prediction error time series with average absolute error NMAE 5.3 % of installed capacity. Average (absolute) error of 5.3 % corresponds to 21 % of average power and 7.7 % corresponds to 30 % of average power. These larger error metrics 21 % and 30 % give the (absolute) sum of prediction errors as % of yearly produced wind energy – which is the amount of energy that needs to be balanced in balance settlement.

The examples in this paper were made with the 3 hour ahead prediction error time series.

This 3-hour-ahead prediction data was chosen here to represent future forecast error of large scale distributed wind power in Finland from day-ahead predictions, as an assumption that in ten years time improved forecasting techniques will lower the average forecast error to about 5.3 % of capacity. The latest results from large-scale, distributed wind power prediction errors from Denmark and Germany are close to 6 % of capacity [8]. It is also notable that the results in this paper are for a well distributed wind power in Finland – for a producer with a single site the prediction errors and thus also balancing costs would be considerably higher [1].

Imbalance settlement prices from 2004 and 2005 from the Nordic market were used together with average prediction errors (up and down) to calculate the imbalance costs for wind power producers with one and two-price system. Average prices in years 2004 and 2005 are presented in Table 1.

Table 1. Years 2004 and 2005 average prices

	Average system price	Average SPOT-price for Finland	Average additional up-regulation price	Average additional down- regulation price	
2004	29.0	27.7	2.9	4.6	€/MWh
2005	29.3	30.5	6.3	5.6	€/MWh

In addition to up- or down-regulation payments, the volume price (0.7 €/MWh) has been added to balancing costs so for 2004 average price calculations 3.6 €/MWh and 5.3 €/MWh have been applied. The prices in 2004 have been quite low compared to what they are today. This is why the prices in this paper for balancing are low – however, as we present comparisons, the price level as such is not so important.

For system net imbalance, hourly data for 2004 from the Finnish TSO Fingrid's web pages was used. This was combined with up-scaled wind power prediction error data to analyse the impact of different amounts of wind power to system imbalances in Finland. The data for hourly transmission amounts between Finland and Sweden in 2004 were used to determine when there would be a bottleneck situation with wind power. In the calculations it was noted that transmission capacity can be exceeded by 100 MW, which is reserved as a system security margin [15]. In [15] most of this paper's results and methodologies are presented in more detail.

4 Payments for wind power producers

Hourly time series of prediction errors for year 2004 (average error 5.3 % of capacity) was up-scaled to correspond 500, 1000, 2000 or 4000 MW of wind power (4000 MW represents a 10 % wind power penetration, as % of gross demand, electrical energy, in Finland). Forecast errors of wind power were superimposed to time series of year 2004 real system net imbalance.

Payments for wind power producers caused by one or two-price system were calculated by two different methods. In the first method, average regulating power prices from years 2004 and 2005 were applied, see equations (1-2). The impact of wind power on the regulation market prices used for imbalance prices has not been taken into account here. The second method takes into account the impact of wind induced demand to imbalance prices assuming linear relations between up- or down-regulation price and regulation demand.

4.1 Payments with average regulation market prices

For the first method using average regulation market prices, equation (1) is applied for two-price system and equation (2) for one-price system.

$$C_2 / Q = \underbrace{[\alpha e P_{up}]}_{\text{Part 1}} + \underbrace{[(1-\alpha)e P_{down}]}_{\text{Part 2}} + \underbrace{[P_{vol}]}_{\text{Part 3}} \quad (1)$$

$$C_1 / Q = C_2 / Q - \underbrace{[(1-e)(\alpha P_{up} + (1-\alpha)P_{down})]}_{\text{Part 4}} \quad (2)$$

In equation (1) part 1 calculates the payments (€/MWh) for up-regulation demand and part 2 for down-regulation demand. Part 3 denotes payments caused by volume price. In equation (2) part 4 calculates financial benefit for wind power users caused by prediction errors that reduce the system imbalance (see Fig 1). Above, P_{up} is up-regulation price, P_{down} is down-regulation price, P_{vol} is fixed volume price (0.7 €/MWh) and α is the share of up-regulation volume in the market, which was 78 % in 2004 and 59 % in 2005. C is cost in euros, Q is the total prediction error (MWh) of wind power which is managed in balance settlement and e is the share of prediction error that increases the total imbalance of the system (see Fig 1).

Here a prediction error time series with average absolute error of 5.3 % of installed wind power capacity was applied. When system net imbalance time series was superimposed to wind prediction error time series, the outcome was that imbalances increased. For example, when prediction error time series of 500 MW wind power capacity was superimposed to the system net imbalance time series, 57 % of the prediction errors increased the net imbalance and 43 % decreased it.

When adding more wind power, also more of the wind power imbalances were increasing the net imbalance for the system: share was 65 % of imbalances for 1000 MW, 74 % for 2000 MW and 83 % for 4000 MW wind power capacity. The shares are marked into most of this paper's figures. In Fig 2 and in Fig 3, 50/50 means that in case where there is very little wind power, the imbalances are distributed 50 % increasing the system net imbalance and 50 % decreasing the system imbalances. Results from equations (1-2) are presented in Fig 2 and Fig 3. Direction of prediction error is set to the figure 2's and 3's labels, to demonstrate the impact of the prediction error's direction on payments. In the figures 5, 6, 7 and 8 the direction is in parenthesis and wind power capacity is highlighted. Thus the effect of a capacity on payments is emphasised.

It can be clearly seen from Fig 2 that the two-price system for imbalances means more payments for wind power producers. This is generally true also for other production forms, or for consumption, as long as any individual actor contributes little to the system net imbalances. When the penetration level of wind power increases wind power prediction errors start to affect net system imbalances more. This can be seen clearly calculating the percentage of wind power imbalances (volume) that are increasing the system net imbalance, this is denoted by e . Here this increasing share gives increasing imbalance payments for wind power producers.

Fig 2. Payments (€/MWh) for wind power producers with year 2004 average regulating power prices. The sum of (absolute) prediction error is 21 % of yearly produced wind energy (average error 5.3 % of wind power capacity). The results are for a distributed wind power in Finland – for a producer with a single site the payments would be higher.

Fig 3. Payments for wind power producers with year 2005 average regulating power prices. The sum of (absolute) prediction error is 21 % of yearly produced wind energy (average error 5.3 % of wind power capacity). The results are for a distributed wind power in Finland – for a producer with a single site the payments would be higher.

In Fig 3 the payments are higher than in Fig 2 because year 2005 average regulating power prices are higher than year 2004 average prices. The 2005 prices are included here to demonstrate that the year 2004 regulation power prices are rather low. The prices have been higher in recent years than in 2004. However, the basic mechanism with increasing payments for wind power with increasing penetration level remains similar for both of the years.

4.2 Payments using regulation market price that increases with increased imbalances

For the second calculation method, the payments were calculated using rough linear estimates of the relation between regulating power quantity and the price that is based on the results in [16]. When there are bottlenecks of transmission (congestion), Finland will be a separate price area and the regulation has to be acquired from Finnish bids to the Regulating Power Market. The regulating power is usually more expensive in Finnish than in common price area due to fewer bids in the market and especially fewer hydro power available to bid (the Nordic hydro power is mostly in Norway and Sweden). Increasing the demand of regulating power during hours when the regulation has to be acquired from Finland alone will have a more pronounced impact on the prices. This is because the regulating power in Finland is quite scarce and adding more regulating power will be more expensive. This is why a more strong/steep correlation (higher curves in Fig 4) has been used to determine the imbalance prices in bottleneck situations. However, in Fig 4 common price estimations $P_a(Q)$ and $P_b(Q)$, where Q is the corresponding regulation volume, were based on scatter plots in [16]. In bottleneck situations Finnish area price estimations, $P_c(Q)$ and $P_d(Q)$, were based on Finland's regulation cost in [16]. Also, all linear quantity price relation estimations are performed visually [15].

Fig 4. Regulation price as the difference between SPOT-price and regulating power price. The scatter plot is from [16] and the linear price-quantity relations used in this paper are marked with lines.

The linear estimations of regulation price used here are rough estimates. First of all, the real market prices have a scatter and are not strictly linear. Also, the regulating power price in Fig 4 is determined by demand of Finland, Sweden and South Norway but in this investigation it is assumed that only the demand for balancing from Finland determines the price. This is why the price level is very low and should not be taken as a result, only the comparison results are of importance. The price level with this approach has been compared with real prices of imbalances in Section 4.3 to show that they are reasonably close to year 2004 data.

Imbalance prices for the payments of wind power producers were calculated from $P_a(Q) = 0.011 \times Q$ and $P_b(Q) = -0.015 \times Q$. The amount of total imbalance Q was determined by adding wind power to net imbalance time series. Also volume costs are added; the volume costs in

Finland are 0.7 €/MWh for all prediction errors. Here are two examples how the payments was calculated:

1) If the imbalance for wind power for the hour was 20 MWh (down-regulation) and system net imbalance for the hour was 50 MWh without wind power (need for down-regulation), the system net imbalance with wind power would be 70 MWh. Then down-regulation price would be $0.015 \times 70 = 1.05$ €/MWh, that is difference between imbalance price and SPOT-price. Wind power producers would then pay the wind power imbalance $20 \text{ MWh} \times 1.05 \text{ €/MWh} + \text{volume cost}$ (in both pricing systems).

2) In one-price system wind power producer might benefit economically when producer's imbalance would reduce the system net imbalance (up/down regulation need): if imbalance for wind power for the hour was 10 MWh (up-regulation) and system imbalance for the hour was 50 MWh without wind power (need for down-regulation) then the system imbalance after wind power would be 40 MWh and regulation price $0.015 \times 40 = 0.6$ €/MWh. Then wind power producers would gain $10 \text{ MWh} \times 0.6 \text{ €/MWh}$ but still have to pay volume cost for the 10 MWh.

The total payments for wind power after hour-by-hour calculation was divided with total wind power production and final result was presented in the form of total payments (€) per produced wind power energy (MWh). Below, Fig 5 shows the resulting total payments for corresponding wind power capacities. There, the payments from using two-price system are consistently higher than those from one-price system. However, the difference becomes smaller (relatively and absolutely) as the wind power capacity in the system increases: the

more wind power influences the direction of system net imbalance the closer the payments of one-price system are with the payments of two-price system. This is as expected, as both one- and two-price system treat wind power imbalances the same way during the hours when wind imbalance increases (is to the same side as) system net imbalance.

Fig 5. Payments for wind power calculated assuming linear relations $0.011 \times Q$ and $-0.015 \times Q$ for up-and down regulation prices between regulation price and quantity in 2004. The results are for a distributed wind power in Finland – for a producer with a single site the payments would be higher.

To demonstrate the significance of payments in 2004, the ratios between the costs in Fig. 4 and Fig. 5 and average SPOT-price for Finland (see Table 1) depict the relative values of the payments in Table 2. The values varies from 0.9 % to 4.2 %, increasing with added wind power capacity.

Table 2. Payments as a ratio of average SPOT price for Finland in 2004

Average prices; one-price	Average prices; two-price system	Prices from linear relation;one-price	Prices from linear relation;two-price
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	system/SPOT FIN	payments/SPOT FIN	system/SPOT FIN	system/SPOT FIN
500 MW	0.9	2.0	1.1	1.4 %
1000 MW	1.3	2.1	1.6	1.8 %
2000 MW	1.7	2.4	2.4	2.6 %
4000 MW	2.2	2.6	4.2	4.3 %

4.3 Comparing the payments with previous calculations

From previous work the balancing costs for aggregated wind power in Finland was 0.62 €/MWh in 2004 [1]. This was estimated using the actual time series data for year 2004 prices instead of average prices (equations 1-2), and with forecast error of 31 % of average production. Here using the average prices for 2004 gives somewhat higher payments (0.78 €/MWh, Fig 2, for 21 % prediction error) than using the actual hourly price data for year 2004. In 2004, only 40 % of time the imbalances caused extra payments, this also explains the difference, as here 50 % was used as basic assumption for situation with low penetration of wind power. Wind penetration level in Finland is less than 1 %.

For West Denmark, the hourly analysis for year 2001 data gave as a result balancing costs of 2.3 €/MWh [2]. For year 2002 the balancing cost was 3 €/MWh [11]. In West Denmark, wind power was already producing about 20 % of electricity in 2001. This means that wind power imbalances are affecting the market during those hours when the SPOT market is divided into area markets. In West Denmark the imbalances of wind power causes balancing payment about 70 % of time.

In Sweden balancing costs ranging from 10.7 to 37.5 SEK/MWh or 1.15 to 4.03 €/MWh (bases on June 1st 2007 interbank conversion rate) have been estimated for the actors, corresponding to differences in their sizes, how distributed wind power is sited and

differences in price assumptions for balancing market [10]. The lower value (representing a distributed wind power as in this paper and not taking into account future price increases) is more relevant to comparison for the results presented here. This is somewhat more than estimated here, or in [1]. This is probably due mostly to the fact that we use a future estimate for prediction errors (average error 5.3 % of installed capacity). Also, the Swedish analysis applied high forecast error estimates that may overestimate their imbalance costs [10].

It is interesting to check the linear price-quantity assumption against the previous result using actual hourly balancing market price data. The imbalance payment 0.62 €/MWh (for 31 % prediction error) can be compared with 0.40 €/MWh (for 21 % prediction error) in Fig 5. For the result 0.62 €/MWh bottlenecks resulting in price areas are considered but for 0.40 €/MWh they are not. Therefore the 0.40 €/MWh would be closer to 0.62 €/MWh in case where the bottlenecks would be considered and the forecast error would be increased to 31 %. The wind power capacities are also different for the results. But this does not increase the difference in the results substantially: in Fig 5 increase in payments is 0.10 €/MWh from 500 MW to 1000 MW, likely it is much less from 82 MW in 2004 to 500 MW. Thus it can be concluded that the payment level for 500 MW wind power is in accordance with the previous study. The uncertainty in results is likely to increase with wind power capacity.

It is also important to notice that when wind penetration is large enough to start affecting the system net imbalances, this will result in increased payments for the producer and also make an incentive to correct at least the largest errors when updated forecasts appear some hours before delivery. This has not been taken into account and would change the result of

this work.

5 System costs for power system

With system costs we refer to cost that system operator TSO pays for the regulation, which is according to the costs of the most expensive regulation opportunity activated in the hour. System costs could also be calculated as a sum of the costs of all regulation performed, of which a lot can have much lower costs than the marginal plant. This would reduce the system costs and thus make the payments by the producer look even higher compared with costs. However, we are here using the existing convention from the Nordic regulation market, where TSOs pay the same price to all the activated bids, determined by the last bid accepted.

Prediction errors of large amounts of wind power increase system net imbalance during most of the hours. Increased system net imbalances cause additional costs for power system. To estimate the costs caused by increased system net imbalances for Finland, forecast errors of different amounts of wind power was superimposed to time series of year 2004 real system net imbalance. As in Section 4, the same hourly up-scaled time series of prediction errors for year 2004 (average error 5.3 % of capacity) were applied here too. The system costs were calculated by two different methods: using average up- and down- regulation prices and using a linear relationship between the regulation price and quantity.

5.1 System cost estimated by average balancing prices

Average regulating power prices of year 2004 were applied for the net imbalances of Finland, before and after wind power (the prices are presented in Section 2). The calculation

was made by calculating the cost for all imbalances requiring up-regulation with average balancing price of up-regulation and adding to that the cost for all imbalances requiring down-regulation with average balancing price of down-regulation. This was done first without wind and then with wind and the difference was presented as the costs for wind power. Final costs are presented in the form of costs (€) per produced wind power energy (MWh). The results are presented in Fig. 6 and Table 3.

System operators balance the system net imbalances in Regulating Power Market, which is a common balancing market for the four Nordic countries. Using average up- and down-regulating prices does not take into account the fact that when more regulating power is used, also the imbalance price will increase. Thus this method will underestimate the system costs.

5.2 System cost estimated by linear price/quantity relationship

The rough estimation between quantity and price of regulating power was applied to system costs in two ways: first assuming the Nordic price curve for all hours and second taking into account higher balancing prices during bottleneck situations [15]. In Fig 4, lines $-0.015 \times Q$ and $0.011 \times Q$ are used for hours when there was no bottleneck and lines $-0.036 \times Q$ and $0.036 \times Q$ when there was a bottleneck situation. To determine when there was a bottleneck year 2004 hourly transmission time series was used. Wind impact to bottlenecks was estimated for the “with wind” cases using the year 2004 hourly transmission situation with wind imbalances added. The bottlenecks between Finland and Sweden occurs usually less than 10 % of time. In the year 2004 data bottlenecks occur 7.5 % of all hours.

However, wind power will impact these bottlenecks, here the forecast errors due to 4000 MW wind power increased the bottlenecks to 17.8 % of the hours.

The increase in system costs due to wind power prediction errors are presented in Fig 6 for the three calculation methods. Here the wind power prediction error time series with average error of 5.3 % of capacity is applied. In Fig 6, the black bars show the costs when bottlenecks have not occurred (only lower lines in Fig 4 are used); stripes above the black bars show the difference in costs when higher costs due to bottlenecks have been taken into account. Grey bars costs are calculated by applying year 2004 average regulating power prices. As expected, the average prices give considerably lower estimates. The difference increases as wind power penetration increases, indicating that with higher penetration levels average prices should not be used when making the estimates of wind power to system costs; that's because average prices don't increase due to increasing demand for regulation power.

The assumption that there are no bottlenecks reflects a case when new transmission capacity between Finland and Sweden is installed to reduce the bottleneck situations (there are currently plans by the TSO to increase the transmission capacity).

Fig 6. Increase in costs divided by amount of wind power for balancing net balance deviation in Finland for increasing amount of wind power when wind power prediction error is on average 5.3 % of capacity. Stripes show the difference in system costs when the bottlenecks in transmission capacity between Finland and Sweden have been taken into account as increasing regulation price-quantity relation.

In Table 2 the significance of payments was demonstrated. In Table 3 demonstration is done for the Fig 6 's system costs. Here values varies from 0.5 % to 4.3 %.

Table 3. System costs as a ratio of average SPOT price for Finland in 2004

	Average costs/SPOT FIN	Costs from <i>Lower</i> linear assumption /SPOT FIN	Costs from <i>Higher</i> linear assumption /SPOT FIN	
500 MW	0.5	0.7	0.7	%
1000 MW	0.7	1.2	1.2	%
2000 MW	0.9	2.0	2.2	%
4000 MW	1.2	3.7	4.3	%

In linear assumptions the relative increases in the ratios are almost one-to-one with relative increases in capacities, but in average ratios the increases are less. For the payments calculations the calculation method was shown to give similar results for small penetration levels compared to previous results using actual balancing market price data (Section 4.3). For system costs we are actually only presenting differences in costs, for imbalances before and after wind power is added. This will reduce the uncertainty that the rough methodology will bring about. The price-quantity relations used in this work are quite steep, which means that we try not to underestimate the costs due to wind power.

5.3 Comparing the system costs with previous work

The system costs assessed here gives one estimate of the impact of wind power to balancing costs for the system. Here the actual time series of the net system imbalance before wind has been used, and the wind forecast error induced imbalances to net system imbalances have been superimposed to this time series, using synchronous wind and system imbalance data, but up-scaling the wind data. The day-ahead forecast error has been assumed to be balanced during the operating hour, with load following reserve from the Nordic balancing market. The wind power penetration level in this study has been from 1 % to 10 %, of electrical energy (yearly wind power production divided by yearly electricity consumption).

In other studies, other methods have been used. In [8] the summary of 7 more recent studies give the range of 0.2 €/MWh to 2.7 €/MWh at 10 % wind penetration. The Greenet study for Norway, Finland and Sweden give about 0.5 €/MWh balancing costs. This is derived by simulating the Nordic power system, at an hourly level, with wind power forecast

errors, and calculating the differences of operating costs of the system before and after wind power [17 : Meibom et al, 2009]. The balancing cost of 2 €/MWh calculated for Finland in [18: Holttinen, 2005] assumes a cost for increasing regulating capacity, and this is why it is higher than the cost here (assuming only operating costs for the power plants at the balancing market). The Greenet study [17] for Germany as well as the UK study [19: Strbac et al, 2007] result in a higher balancing cost of 2.4-2.7 €/MWh. This is due to more expensive (thermal) regulating capacity (in the Nordic countries the regulating bids to balancing market come mainly from hydro power plants). For the Irish study [20], 0.2 €/MWh, only the hourly variability of wind power has been taken into account, not the forecast errors. This comparison shows that the results in this paper are in line with other calculations for the Nordic, hydro dominated system, but that the estimated increase in system costs for other, thermal systems, can be considerably higher.

6 Comparison of costs

The costs for system operator presented in Section 5 and the costs for wind power users presented in Section 4 are compared in Fig 7. In Sections 4 and 5 the same time series was used, thus the results are comparable.

Fig 7. Comparison between payments for wind power producers and system costs, using average balancing prices. The system costs with black bars are calculated with same up- and down-regulation prices as the one- and two-price system costs for the producers. The results for one/two-price system are for a distributed wind power in Finland – for a producer with a single site the costs would be higher.

According to Fig 7, system costs of wind power are lower than what wind power producers pay as imbalance costs, when using average up- and down-regulation prices. In Fig 7 the system costs and payments are calculated by using average regulation prices,

therefore the results are rather rough.

In Fig 8 both costs are calculated considering the quantity price relations $-0.015 \times Q$ and $0.011 \times Q$ in Fig 4; and volume costs are added to all wind power producers' imbalances. This method assumes that bottlenecks do not occur. The linear assumption is theoretical, so the price level is not to be looked at but the comparison of costs.

Fig 8. Comparison between payments for wind power producers and system costs. It is assumed that bottlenecks do not occur and all costs are calculated using linear relations ($-0.015 \times Q$ and $0.011 \times Q$) between regulation power price and quantity to determine regulation power price. Volume costs of 0.7 €/MWh are added for wind power producers. The results for one/two-price system are for a distributed wind power in Finland – for a producer with a single site the costs would be higher.

According to both Fig 7 and Fig 8 difference between one-price system payments and two-price system payments reduces as wind power penetration increases; that is because the direction of prediction error depends on wind power capacity. In Fig 8 the system costs almost double with 2000 MW wind power compared with 1000 MW wind power and again when increasing wind power from 2000 MW to 4000 MW. The price levels in Fig 7 and in Fig 8 cannot be directly compared, as the linear and average price assumptions are theoretical.

In this paper it is assumed that system costs should correspond with payments for wind power producers. According to this assumption the payments are higher than they should be (even if one-price system is applied). Therefore applying one-price system for wind power producers could be reasonable. Naturally all TSO's expenses can not be considered in this paper. These kinds of costs are for example running and maintenance of balance settlement as well as payments for frequency control (instantaneous) reserve and disturbance reserve.

7 Summary and discussion

In this paper the imbalance costs of wind power producers and the effect of wind power forecast errors on net system imbalances in Finland are described. The link between what is the cost that wind power imbalances actually cause to power system and what is the cost allocation to wind power producers through balance settlement payments is investigated. Two balance settlement rules for the imbalance payments for producers were analysed: a one- and a two-price system.

Here rough estimations about balancing prices are applied which means that the

comparisons are the relevant results, and the price levels as such should not be referred to. For imbalance payments, a comparable result from a previous study showed that the result in this work is in accordance with the previous results at low penetration level. For increases in system cost, only differences due to wind power were estimated, which reduces the uncertainty of the original pricing method.

The two-price system for imbalances makes the imbalance costs for producers clearly higher than one-price system, especially with lower wind power penetration when wind power does not affect the system net imbalances significantly. Both systems reflect the increase in costs as wind penetration increases. Increasing penetration level increases wind power prediction errors and they start to affect net system imbalances more. This can be seen also as the percentage of imbalances that are increasing the system net imbalance. According to comparison, the increase in system costs due to wind power is lower than imbalance payments for wind power producers. It is important to note that in this work wind power production was assumed distributed along the Finnish coastline – the imbalance payments for a single wind park production would be considerably higher than the costs presented here especially if two-price system is used. Therefore it could be reasonable to apply one-price system for wind power producers.

Increase in system balancing costs due to wind power and imbalance payments for wind power producers come relatively closer to each others when the wind power capacity increases. However, the payments exceed the system costs in all the studied cases.

It is also important to notice that when wind penetration is large enough to start affecting

the system net imbalances, this will result in increased payments for the producer and also make an incentive to correct at least the largest errors when updated forecasts appear some hours before delivery.

The system operators have also other costs than the direct cost from the regulating power market, namely the cost of making the balance settlement and the cost of reserves for frequency control, including contingency/disturbance reserve costs. These costs were not assessed in this work. These costs could also be gathered from a fixed fee or tariff from all producers and consumers.

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