Impact of large scale wind integration on power system balancing

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***Abstract* — With an increasing wind power penetration, more generation intermittency will be added to the power system, requiring higher flexibility and thus more regulating reserves. Based on high resolution numerical weather prediction models and wind speed measurements, the actual and the forecasted wind power production is simulated for five scenarios covering the years 2010, 2015 and 2020. These scenarios are taken as an input to an integrated northern European market model, analyzing the procurement of regulating reserves and their activation. Further on, the possible benefit of integrating the northern European regulating power markets for handling the intermittent production is investigated.**

***Index Terms*—Wind Power, Forecast Error, Reserve Procurement, Power System Balancing, Market Integration**

I. Nomenclature

EMPS	– EFI's Multi-area Power market Simulator
IRiE	– Integrated Regulating power market in Europe
MAE	– Mean Average Error
NMAE	– Normalized Mean Average Error
WPP	– Wind Power Production
WV	– Water Value

II. Introduction

The intermittent production on all time scales is one of the major challenges when it comes to large scale wind power integration. In a liberalised market WPP, based on forecast scenarios, can be traded in the day-ahead market. However, short term deviations, resulting in system imbalances, have to be traded in the real time or regulating power market. For WPP simulations the whole balancing area has to be considered, as smoothing effects in large geographical areas reduce the requirement for regulating reserves [1]. In Fig. 1 the annual duration curves for load and net load (load minus WPP) variations, equivalent to the delta between consecutive hours, are shown. The differences between the maximum values of the curves indicate the requirement of additional reserves when adding the variability of wind, due to hourly production changes [2]. Besides these increased production changes, there are wind forecast errors (Fig. 2), resulting in a difference between planned and actual production. These deviations need to be compensated by the activation of regulating reserves, available to the power system.

The procurement and possible subsequent activation of these regulating reserves is done within regulating power markets. In order to study the effects of WPP on system balancing the reserve procurement and system balancing in the northern European area is simulated and the according costs are estimated. This is done for national regulating power markets as well as an integrated northern European market, to estimate possible benefits of exchanging regulating reserves as well as energy.

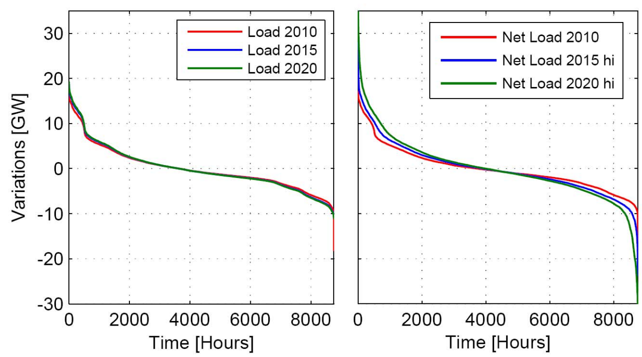

Fig. 1 Duration curves of annual load and net load variations

III. Wind Power

A. Modelling Wind Power Production

The simulated real time WPP is based on a mixed input data set including wind speed measurements from more than 200 gauging stations and input values from the high resolution numerical weather prediction tool COSMO EU [3], [4]. In the analysis wind speed data of 2010 is used. To avoid scaling errors, which occur when scaling up single wind farm productions to the installed capacity in an area and to incorporate the effects of geographical smoothing, the production of each of the 3200 WPP facilities included in the data set is modelled individually. Surface roughness length, topography, turbine characteristics for on- and offshore facilities as well as future WPP curves are included in the simulations [3].

The WPP forecasts, being 3h and 24h ahead, are solely based on COSMO EU's wind speed data.

The WPP scenarios used in the here presented analysis are shown in Table I. These scenarios are based on the expert knowledge and assumptions from the respective national wind energy agencies or local research institutes. The scenarios for 2015 and 2020 were collected from the TradeWind project [5].

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To match the installed capacity of the future scenarios each wind power facility in the 2010 data set is scaled up. Due to the comprehensive and geographically dispersed data set used in the simulations, the effect of scaling errors for the 2015 and 2020 scenarios is minimized.

TABLE I
INSTALLED WIND POWER GENERATION CAPACITY [MW] 2010, 2015 & 2020

Areas	2010	2015		2020	
		Low	High	Low	High
Norway	545	940	4000	1380	6600
Sweden	1250	2250	5700	4000	10 000
Finland	350	600	1900	1100	3000
Denmark	3700	3900	4750	5000	6000
Germany	24 900	27 800	43 100	34 600	57 300
Belgium	1000	1100	2000	1300	2950
Netherlands	2800	4400	7000	5400	10 400
Sum	34245	40 990	68 450	52 780	96 250

B. *Forecast Error*

Due to the highly sophisticated numerical prediction models, the NMAE 24h ahead only amounts up to about 3.7% system wide for the 2020 high wind scenario. This is equivalent to a MAE of about 3500MW, see Table II. Correspondingly, a further increase in accuracy is noticeable for the 3h forecast, reducing the NMAE to about 0.7%.

TABLE II
MEAN FORECAST ERROR

	2010	2015		2020	
		Low	High	Low	High
MAE 3h [MW]	218	272	524	406	883
NMAE 3h [%]	0.6	0.7	0.8	0.7	0.9
MAE 24h [MW]	915	1198	2172	1719	3596
NMAE 24h [%]	2.6	2.9	3.1	3.2	3.7

Even though the values for MAE and NMAE constitute a rather optimistic view on the wind forecast error and the hence necessary regulating resources in the system, Fig. 2 shows that there are considerably high wind forecast errors, which especially occur before and after storm fronts. The largest deviations in the 2020 high wind scenario reach an absolute value of about 50 GW. This illustrates the challenges the system is confronted with by adding large amounts of intermittent wind power.

IV. MARKET MODEL

The general structure of the market model used in the presented analysis is depicted in Fig. 3. The analysis consists of three stages. It simulates an integrated northern European regulating power market, which is based on a common day-ahead market, including the Nordic countries Finland[1], Denmark, Norway, Sweden and the continental European countries Germany and the Netherlands as shown in Fig. 4 at the stage of 2010.

[1] Finland is not included in the simulation of the regulating power market. However, due to the geographic location it has only little impact on the simulated regulating reserve and energy exchange.

The model structure consists of two general parts, represented by two different models, which are EMPS and IRiE respectively. The EMPS model is a long- and mid-term optimisation, whereas IRiE has a short-term horizon.

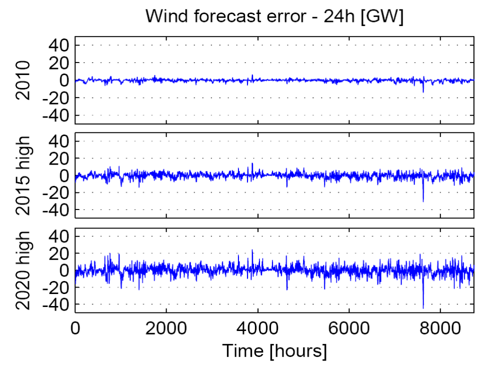

Fig. 2 Hourly wind power forecast error for 24h ahead

A. *Day-ahead market*

The common day-ahead market is modelled with EMPS [6]. This model determines the socio-economic optimal dispatch of electricity generation on a weekly basis, with the possibility of further refinement, assuming perfect market behaviour with a time horizon of several years.

EMPS contains several areas, connected by lines. The transmission lines are modelled by net transfer capacities including linear losses. The output of this model is the optimal generation dispatch, area prices and water values for the Nordic reservoirs. Water values are the opportunity costs of the stored water and are used as marginal production costs for the hydro power plants [7].

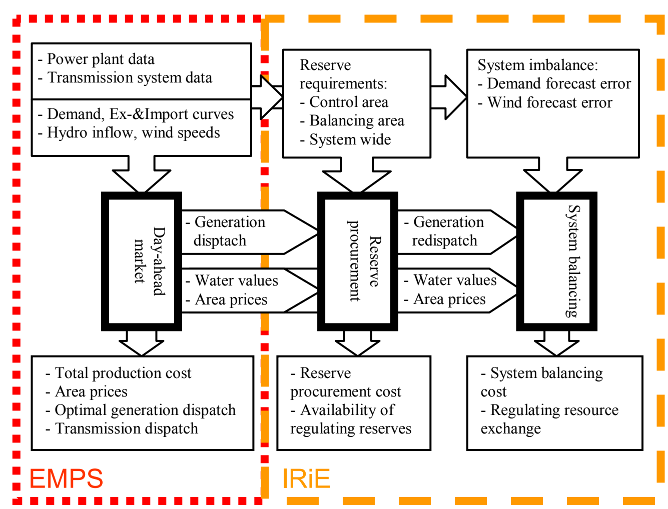

Fig. 3 Model structure and workflow [6]

B. *Reserve Procurement*

During the reserve procurement the optimal day-ahead generation dispatch is changed in order to fulfil given reserve requirements per control area. Here, regulating reserves can not only be procured in the own control area, but also externally. As the reserves are procured after the day-ahead market clearing, the remaining transmission capacity is taken into account. The reserve procurement is done for each individual hour, considering the start-up state of thermal units.

The procurement is done in a socio-economic optimal way, based on marginal production costs of the thermal units and water values for the hydro power plants, including start-up costs and efficiency losses at part-load operation of generation units [8].

C. System Balancing

The system balancing, based on activating the least-cost regulating reserve, compensates for the system imbalance including the wind forecast error. The available transmission capacities are likewise taken into account. The balancing is done for each 15 minutes using recorded imbalances from the respective control areas as an input as well as the wind forecast errors. The costs for balancing the system are estimates for upward and downward regulation based on the production costs of thermal units and the water values for hydro units [6].

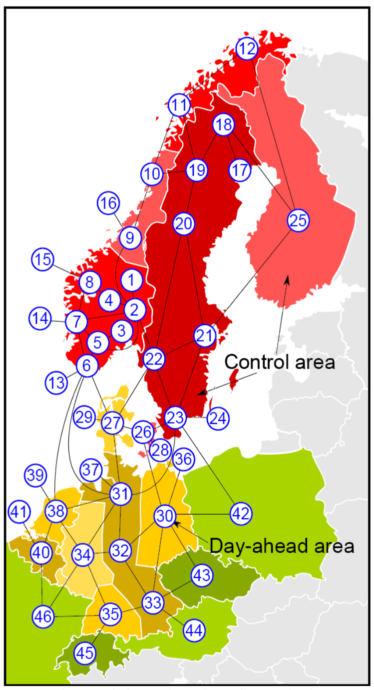

Fig. 4 Geographic overview of day-ahead and regulating power market model

V. Case Studies

In order to study the effects of large amounts of WPP on the system operation, several cases are defined. The first two cases represent the system state of 2010. One includes the imbalances of the currently installed WPP. The other called "no wind" excludes those imbalances in order to analyse the impact of intermittent WPP. Furthermore four cases are defined, which are based on the WPP scenarios for the years 2015 and 2020. For both of the years a scenario with a high and a low capacity of installed WPP are included. The installed wind capacities for the cases can be found in Table I. For all the cases a system configuration as of 2010 is used.

In addition to the different scenarios of WPP, two different cases of the reserve procurement as well as the system balancing are defined. These cases are no market integration and full market integration.

The case **no market integration** shall represent the current state of the system. In this case required regulating reserves have to be procured in each country. As can be seen in Fig. 4 Norway and Germany are split in several control areas. In these countries reserve requirements are defined per control area, however, the procurement can be done country-wide, taking into account available transmission capacities. Regulating reserves likewise can only be activated in the own country and not be exchanged.

Full market integration describes a future state in which all the regulating power markets in northern Europe are fully integrated. Besides the procurement of reserves in the own country, they now can also be procured in the whole modelled system. This exchange can only be done if there is free transmission capacity available after the day-ahead market clearing in order to assure the possible activation of these exchanged regulating reserves. Like reserve capacities, regulating energy can be exchanged system-wide in this case. Again, the available transmission capacity is taken into account. These both exchange possibilities result in the procurement of the system-wide cheapest reserves as well as the activation of the least cost reserves.

VI. Results

With the given installed wind generation capacity scenarios the forecasted and the actual WPP are calculated and applied to the market model, analysing different market scenarios.

A summary of the results for the previously defined cases can be found in the following Tables III and IV. In Table III results for the current state of the system with no market integration are presented. This means the procurement and the activation of reserve capacity is done in each single country in order to balance the supply and demand.

In order to be able to balance the system with increasing WPP, it is estimated that there is a rise in reserve requirements in all the countries. Thus, there also is a higher cost for the reserve procurement in the future scenarios. The same reserve requirements are used for the low and high wind scenarios, to make the system balancing comparable.

With a higher WPP penetration the system imbalance increases significantly. The inclusion of the wind forecast error already results in a doubling of system imbalance. In the 2020 high wind scenario the imbalance nearly triples compared to the 2010 case. The gross reserve activation is about one third lower than the gross imbalance due to the netting of load and WPP imbalances. The difference in the no wind case results from the internal netting in Germany. With increasing WPP also the reserve activation increases significantly, being likewise nearly tripled in the 2020 high wind case. The escalating activation of regulating reserves is accompanied by an increase of system balancing costs. This cost increase is tremendous in the 2020 high wind case, mounting up to more than 2 bn€.

TABLE III
REGULATING POWER MARKET OUTCOME - NO MARKET INTEGRATION

	No wind	2010	2015 low	2015 high	2020 low	2020 high
Total reserve requirements [MW]	7080		8435		10 675	
	-		-		-	
Procurement costs [M€]	200.2		287.2		551.5	
Gross imbalance [GWh]	10 900	22 216	26 007	42 921	34 946	63 247
Gross reserve activation [GWh]	7771	14 531	16 896	27 485	22 256	43 375
Gross reserve activation in the Nordic area [GWh]	3273	3631	3541	4649	3778	5676
	-	-	-	-	-	-
Balancing costs [M€]	96.0	492.1	595.4	1252.5	750.6	2329.3

TABLE IV
REGULATING POWER MARKET OUTCOME – FULL MARKET INTEGRATION

	No wind	2010	2015 low	2015 high	2020 low	2020 high
Total reserve requirements [MW]	7080		8435		10 675	
Average regulating reserve exchange [MW]	1070		1174		1316	
Procurement costs [M€]	114.7		146.3		245.0	
Gross imbalance [GWh]	10 900	22 216	26 007	42 921	34 946	63 247
Gross reserve activation [GWh]	6068	11 088	12 969	21 412	17 293	34 226
Gross reserve activation in the Nordic area [GWh]	3737	5712	6264	8230	7212	10 139
Regulating energy exchange [GWh]	2355	4660	5515	7470	6821	9581
Balancing costs [M€]	55.6	374.4	448.1	939.9	540.8	1609

Fig. 5 shows the duration curve of the day-ahead market dispatch for the HVDC connectors between the Nordic and the continental European power systems. Shown are the percentiles for 40 different inflow scenarios to the Nordic hydro-based power system. The exchange is the sum over all lines. The difference in the percentiles indicates that there is a net energy export during wet and an import during dry years in the Nordic countries. It can be seen that only during about 500 hours of a year all lines are dispatched at maximum or minimum capacity at the same time. This leaves free capacity for the exchange of regulating reserves as well as energy. Furthermore, even if a line is dispatched at its maximum, regulating reserve exchange on this line in one direction is possible [8].

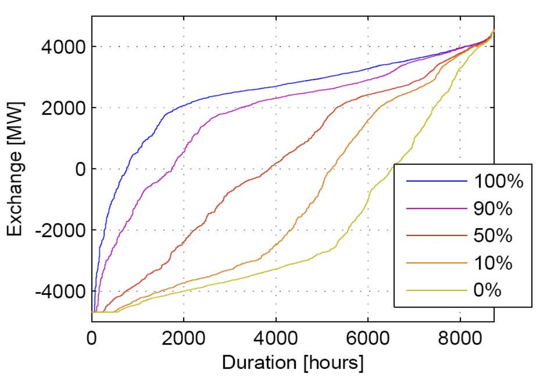

Fig. 5 Day-ahead dispatched transmission of HVDC cables

In order to achieve a more efficient power system operation, meaning in this analysis balancing of production and consumption, an integrated regulating power market is assumed, as described previously. Therefore the above shown remaining transmission capacity is taken into account and regulating reserves as well as regulating energy is exchanged system wide. A summary of the results for the full market integration case can be found in Table IV.

In this analysis, the same reserve requirements are used for the full market integration case, as for the no integration case. Fig. 6 shows the procurement of required upward regulating reserves in 2015. In average 1158MW of upward reserves are exported per hour on the cables between Nordic and continental Europe. These are around 30% of the reserves required in western Denmark, the Netherlands, Germany and Belgium. However, there is only an export of 16MW of downward regulating reserves. Fig. 6 clearly shows, that the main importing country is Denmark with a share of almost 50%. The exporting countries are Norway, Sweden. The continental reserve exchange decreases further inland.

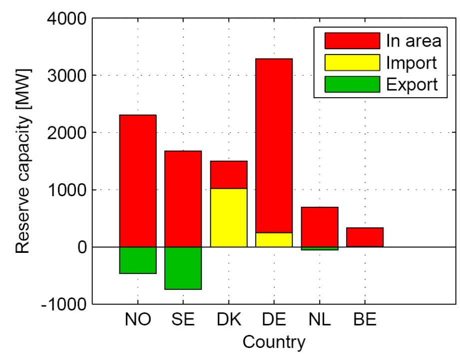

Fig. 6 Country wise procurement of upward regulating reserves with full market integration in 2015

Due to the increasing requirements the procurement costs rise significantly. However, comparing them to the no integration case, it shows that they can be cut down half.

The lower part of Table IV shows the results of system balancing. It can be seen, that the activation of reserves is only about 50% of the actual system imbalances, showing that there is a huge opportunity of netting imbalances of different areas, including the smoothing effect for WPP. Furthermore, 55% (2010) to 30% (2020 high wind) of the reserve activation is executed in the Nordic area. In the no integration case, this share is only 25% to 15% respectively. Comparing the total amount of activated reserves for the 2020 high wind scenario, a 40% increase appears in the Nordic area between no- and full market integration. The increase in the Nordic area and the additional possibility of netting imbalances results in a large reduction of reserve activation in the continent. Fig. 7 shows the comparison of reserve activation for the no and full market integration case in the 2015 high wind scenario. The previously mentioned increase is obvious. Especially in Denmark the activation is reduced to about 25%. Also the reserve activation in the Netherlands and Germany is significant, being about 50% and 40% respectively. However, the reduction in Belgium only amounts up to about 10%. This is probably due to the geographic distance to the Nordic area.

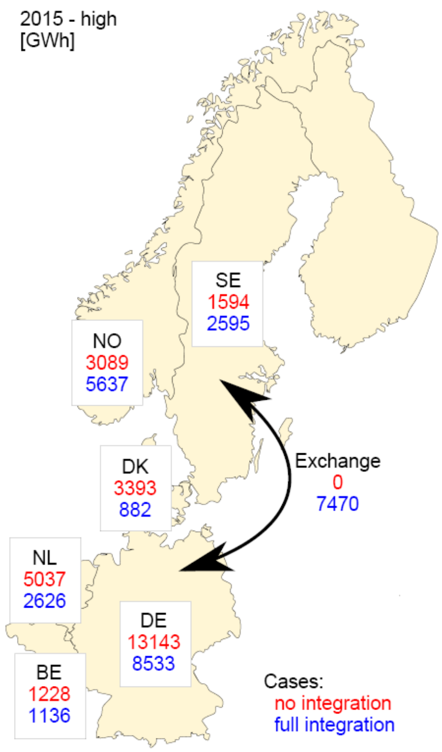

Fig. 7 Regulating reserve activation in the 2015 high wind case for no and full market integration

The duration curves for the reserve activation in the Nordic and the continental European areas in the 2015 high wind scenarios are plotted in Fig. 8. In these duration curves, the increase in reserve activation in the Nordic area is shown too. Besides the general decrease of reserve activation, there are now about 1500 hours in the continental areas without internal activation but solely provided by the Nordic area. These hours probably results in a decrease of load-hours for peaking plants and thus their profitability. This can lead to reserve availability issues.

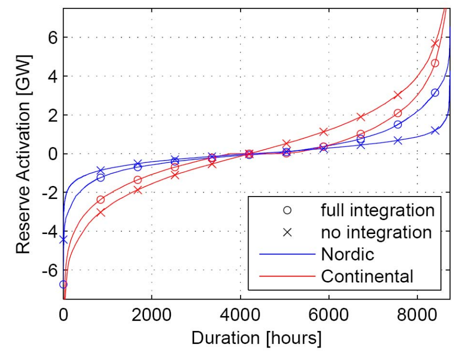

Fig. 8 Duration curve of regulating reserve activation in the 2015 high wind case for no and full market integration

The duration curves for the different wind integration scenarios are plotted in Fig. 9. The gross regulating energy exchange amounts up to about one fifth to one sixth of the total system imbalances. The exchange amount is nearly doubled in the 2020 high wind scenario compared to 2010. In the 2020 high wind scenario the exchange reaches from about -4500MW to 6000MW of regulating energy being exchanged via the HVDC interconnections between the Nordic and the continental European systems.

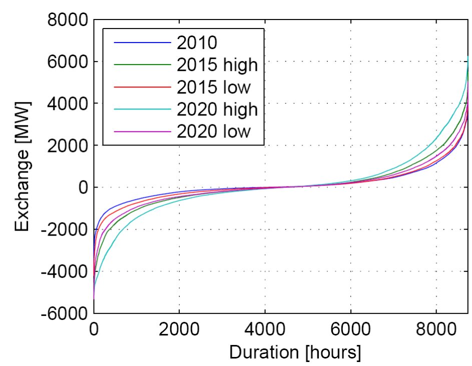

Fig. 9 Exchange of regulating energy from the Nordic to the continental European power system for different WPP scenarios

Fig. 10 shows the exchange of regulating energy during a year in the 2015 high wind scenario. It shows that the exchange of up- and downward regulating energy is almost balanced, indicated by the net exchange of 590GWh in this case, compared to the gross exchange of 7470GWh. This clearly shows that there is no significant export of additional energy to continental Europe, but of production flexibility in order to balance the intermittent WPP.

Finally, there also is a significant increase in the costs of system balancing due to increasing WPP. These are quadrupled in the 2020 high wind scenario, compared to 2010. However, comparing the cost of the no and the full market integration, it can be seen that there are enormous savings coming with the integration of regulating power markets. There is a reduction of about one third in the different WPP scenarios, up to more than 700M€ in the 2020 high wind scenario.

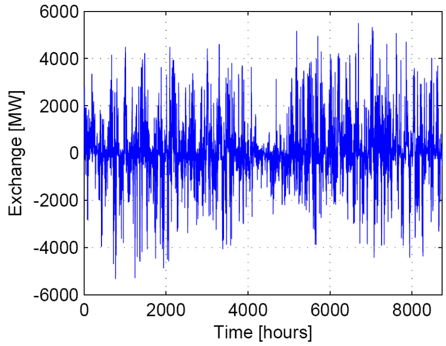

Fig. 10 Exchange of regulating energy between the Nordic and continental European power system for the 2015 high wind scenario

VII. Conclusion

The installation and integration of large amounts of wind power generation capacity into the power system comprises exceptional challenges. Amongst those, system balancing and the procurement of regulating reserves are of outstanding importance. The analyses done in this paper include five independent extension scenarios plus two market models simulating a non- and a fully integrated northern European market.

The regulating power market outcome without market integration shows that even today's installed wind power capacity doubles the gross imbalance and gross activation of regulating reserves and therefore quintuples the balancing cost to about 490 M€. A further triplication of the 2010 results, for imbalances and reserve activation, is observed for the 2020 high wind scenario, culminating in the amount of 2.3 bn€ per annum for system balancing.

Using the possibilities of a fully integrated market with its system wide reserve procurement and exchange possibilities, the procurement costs can be cut down to half of the non integrated case. Almost the same conclusion can be drawn for the balancing costs, being reduced to about 1.6 bn€ in the 2020 high wind scenario.

As most of the reserves are provided in the Nordic area, the exchange of regulating reserves will ascend and become more and more important, while the activation of reserves in continental Europe will decrease by about 1500h in 2015.

The investigated scenarios in this paper confirm that WPP results in a large increase of activation of regulating reserves. However, regulating power market integration with the Nordic power system and thus utilising the flexibility of the Nordic hydro-based power would significantly reduce the activation and hence the cost for reserve procurement as well as the system balancing.

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References

[1] H. Holttinnen, "The impact of large scale wind power production on the Nordic electricity system", *VTT Publications 554*, VTT Processes, Espoo., 2004. 82 p.+ app 111 p

[2] H. Holttinnen, M. Milligan, B. Kirby, T. Acker, V. Neimane, T. Molinski, "Using standard deviation as a measure of increased operational reserve requirement for wind power", *Wind Engineering*, Volume 32, No. 4, 2008

[3] T. Aigner, T. Gjengedal, "Detailed Wind Power Production in northern Europe", *Renewable Energy Conference 2010*, Yokohoma, 2010

[4] Deutscher Wetter Dienst (DWD), www.dwd.de

[5] M. Korpås, L. Warland, J.O.G. Tande, K. Uhlen, K. Purchala, S. Wagemans, "Further Developing Europe's Power Market for Large Scale Integration of Wind Power Grid modelling and power system data", *Tradewind Report*, 2008, http://www.trade-wind.eu/

[6] S. Jaehnert, G. Doorman, "Modelling an integrated northern European regulating power market based on a common day-ahead market", *Proc. of IAEE International Conference*, Rio de Janeiro, 2010

[7] O. Wolfgang, A. Haugstad, B. Mo, A. Gjelsvik, I. Wangensteen, G. Doorman, "Hydro reservoir handling before and after deregulation", *Energy*, Vol. 34, pp. 1642-1651, 2009

[8] S. Jaehnert, G. Doorman, "Reservation of transmission capacity for the exchange of regulating resources in Northern Europe: Is there a benefit?", *Proc. of IAEE European Conference*, Vilnius, 2010

Biographies

Stefan Jaehnert was born in Germany in 1981. He received his Diplomingenieur degree in electrical and mechanical engineering in 2007 from the Chemnitz University of Technology. He is currently pursuing the PhD degree at the Department of Electric Power Engineering at the Norwegian University of Science and Technology (NTNU), Trondheim, Norway. His area of research interest is the integration and operation of multinational balancing markets.

Tobias Aigner was born in Germany in 1979. In 2005 he received his Diplomingenieur degree in mechanical engineering from the technical University in Munich. In 2008 he received his MSc degree in electrical engineering from the University Hagen. From 2005 he was working as a project engineer in the automotive industry. He is currently pursuing the PhD degree at the Department of Electric Power Engineering at the NTNU, Trondheim, Norway. His research interest is the system impacts of large scale wind power.

Gerard L. Doorman received his Electrical Engineering Degree from the Norwegian Institute of Technology (NTH) in 1981 and his PhD from the NTNU (former NTH) in 2000. From 1992, he was with SINTEF Energy Research, working with hydropower optimization, energy systems analysis and market design. Presently he is a professor in electric power systems at NTNU. His current interests are the use of operations research in power systems and power markets, modelling and implementation of demand response and internationalization of balancing markets.

Terje Gjengedal was born in Sandane in 1958. He received a MSc and a Phd in electrical engineering from the Norwegian University of Science and Technology in 1983 and 1987 respectively. He has been working as a senior research scientist, and a visiting professor in the US. While vice president of Statkraft he was working on technology, system and market integration of wind power and other renewable sources. Since 2009 he is the R&D Director at Statnett. Besides he holds a professor position at the NTNU.