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The effect of large scale wind power on a thermal system operation

Hannele Holttinen, VTT Finland and Jens Pedersen, Eltra Denmark.

Abstract—**The impacts of large-scale wind power to a thermal system have been simulated for the West Denmark power system. The West Denmark power system is characterised by large transmission capabilities to both the Nordic and Central Europe systems. The exchange to neighbouring countries has been part of the simulations, with different scenarios for transmission possibilities and prices at the market. Wind power was increased at 10 % intervals, from 0 to 40 % of wind power penetration of gross demand (energy). The goal was to see the change in exchange, surplus power, emissions, thermal efficiency and regulation, due to increasing amounts of wind power.**

According to the simulations, wind power will increase the exports and decrease the imports to West Denmark. The total efficiency of the thermal power and heat production will be slightly increased due to wind power. This is due to better total efficiency for heat and power plants when operating at lower power to heat ratios. However, there will be increased cost per produced MWh for the thermal system, as the wind power penetration gets higher. The value of wind power is near average market price for the first 10 % of wind power, reducing as penetration increases.

At 40 % penetration level, only half of the increased regulation due to wind power forecast errors can be provided by the existing thermal power plants, if there is no transmission capacity and not all CHP plants participate in the regulation. If transmission capacity is included in the simulation, most of the down-regulation will come from exchange. Increase in total start-up costs for the system and decrease in emissions can only be seen for the no transmission case.

Most of the effects of wind power are dissipated to other parts of the power system than the West Denmark area studied, with the transmission possibilities to neighbouring countries available. This is a reasonable result from simulating a small area in a large power system, but also rises discussion in the paper about the ability of scheduling models' ability to capture the effects of large-scale wind power to the system operation.

I. INTRODUCTION

EFFECTS of wind power on power systems include effects on the losses in generation, transmission and distribution, effects on requirement of reserves, as well as reduced fuel usage and emissions. The impacts of wind power depend on the penetration level of wind power in the system as well as the size and inherent flexibility of the system considered.

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Hannele Holttinen is with Technical Research Centre of Finland VTT, P.O. Box 1606, 02044 VTT, Finland (e-mail: Hannele.Holttinen@vtt.fi)
Jens Pedersen is with Eltra, Fjordvejen 1-11, DK-7000 Fredericia, Denmark (e-mail: jpe@eltra-dk)

This paper presents an effort trying to capture these effects by simulating the operation a thermal system with increasing amounts of wind power.

The impact of wind power to the system in the operational time-scale (from several minutes to several hours) is primarily driven by fluctuations in wind generation output. A part of the fluctuations is predictable 2...40 hours ahead. The varying production pattern of wind power is changing the scheduling and unit commitment of the other production plants and use of transmission between regions – either losses or benefits are introduced to the system, compared with the situation without wind. A part of the fluctuations remains unpredicted, or mispredicted. This is the amount that regulation and load following reserves take care of.

Optimised unit commitment (planning the starts and shutdowns of slow-start units) is made more complicated by intermittent output from a wind resource. Even with accurate predictions, the large variations in wind power output can result in conventional power plants operating in a less efficient way. The effect on existing thermal and/or hydro units can be estimated by simulating the system in an hourly basis.

The maximum production (installed capacity) of wind power is many times larger than the average power produced. This means that at a wind power penetration of about 20 % of gross demand, wind power production equals demand during some hours (a 100 % instant penetration). Due to this, 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. Discarded energy occurs only at substantial penetration, and depends strongly on the operational strategy of the power system.

West Denmark is unique in its high penetration level of wind power. Several studies have been conducted, focusing mostly on the discarded energy, or critical surplus production issue. This is especially emphasised during windy, cold periods when there is also substantial share of local, prioritised combined heat and power (CHP) production (Eriksen et al, 2002).

II. DESCRIPTION OF THE SYSTEM, MODEL AND SCENARIOS

A. *West Denmark, Eltra area*

The system simulated is the West Denmark power system, Jutland and Fyn Island, where Eltra is the independent transmission system operator. There has been a high wind power expansion in the area, especially in 1996–2000. This has been accompanied with an increasing decentralised CHP expansion. In Denmark the independent system operators are responsible for the prioritised production (most of the wind turbines and small combined heat and power plants). In 2002, the prioritised production accounted for about half of total demand (20.9 TWh) for the area: Wind 3.8 TWh (18 %) and local CHP 6.7 TWh. The total installed wind capacity is already larger than the off-peak load level, both in winter and summer (Pedersen & Eriksen, 2003). In 2002, wind power production has reached instantaneous penetration of 100 % during one hour, which is unique in the world.

West and East Denmark are not connected, and are part of separate synchronous systems. West Denmark is part of the large Central Europe synchronous system (UCTE) and has sea cables to South Sweden and Norway by automised DC links (Nordel system), thus operating also in the Nordic electricity market Nordpool.

B. Simulation model SIVAEL

SIVAEL is a simulation model for electricity and heat production planning purposes, developed in Denmark (Pedersen, 1990). It is an hourly dispatch/unit commitment model, scheduling the starts and stops as well as unit production rates of power and heat.

Hourly load and heat demand are given as input, based on profiles, and contain no forecast errors. The production system is described in detail, all larger units separately and the smaller units grouped. There are planned revisions for each power plant, as well as stochastic outages according to given probability and average length of outages, modelled as events.

The scheduling is based on minimising the total variable costs, including operational, maintenance and start-up costs of both electricity and heat production. Operational constraints in the optimisation are fulfilling the electricity and heat demands, while taking care of reserve requirements given as input. Unit commitment involves dynamic programming, and there is an iteration loop to fulfil both the local heat demands and the electricity demand for the whole area.

Reserve requirement (spinning reserves, secondary reserves and load following) is taken into account as a given percentage of hourly load. Reserves will be allocated as part load operation of thermal plants.

Wind power production is modelled as an hourly profile (8760 hours). There are separate profiles for land and offshore wind power production. The latest version of SIVAEL has been modified to include forecast errors of wind power. The model uses the predictions for unit commitment and dispatch. The regulation need is calculated as the difference between predicted and actual wind power production, and allocated to either thermal plants or exchange (Pedersen & Eriksen, 2003).

As a result of the simulation, a start/stop schedule for the power plants, as well as their hourly production levels will be achieved. The results include fuel consumption, thermal efficiencies and emissions for all units.

For the hours that the model does not find a solution, because of either too much or too little production for the load, the model will calculate the amount missing, but continue simulating the next hour. In real life these situations would have to be handled by discarding energy or shedding loads. The amount of power that could not be used by the system (surplus production) or the amount of power that the system was lacking (shortfall of production) during one year of simulation is one result of the simulations, indicating issues for further planning in the system.

C. Simulated scenarios and input data

Simulations were run for the year 2010 power system. Electricity demand was assumed to be 23 TWh (increase of 2 TWh) and production capacities were assumed to stay at the level of today (table I). From the standard hourly profiles, peak load of electricity was 4130 MW and heat demand was 5705 MW.

TABLE I
ROUGH DIVISION OF THERMAL PRODUCTION CAPACITY AS MODELLED FOR SIVAEL (SEVERAL POWER PLANTS ARE ACTUALLY MODELLED AS HAVING SEVERAL FUELS).

	Electricity MW_{el}	Heat MW_{heat}	number of plants in SIVAEL
Total	**5012**	**13641**	**53**
Centralised power plants			7
coal	2744	2374	
gas	747	950	
CHP large			9
gas	329	326	
coal	44	105	
renewable	60	111	
CHP small			19
gas	942	1586	
renewable	146	389	
Heat only plants			18
gas	0	3300	
oil	0	4500	

TABLE II
WIND POWER ANNUAL PRODUCTION FOR THE SIMULATIONS. THE DEMAND IS SET TO 23 TWH FOR YEAR 2010.

Wind power % of demand	Wind power on land	Wind power offshore
10 %	950 MW, 2.3 TWh	0 MW
20 %	1900 MW, 4.6 TWh	0 MW
30 %	2560 MW, 6.3 TWh	150 MW, 0.6 TWh
40 %	2560 MW, 6.3 TWh	660 MW, 2.9 TWh

In addition to the thermal capacity in table I, there is 11 MW of hydropower in the system. Wind power for the simulations is presented in table II. Wind power production onshore is based on real large scale production data from Denmark, with scaling to represent a long time average year of 2400 h/a full load hours production. Wind power production for large offshore wind farms is based on wind speed measurements offshore, with full-load hours of 4000 h/a. The scenarios were run with 0 to 40 % of wind power penetration, at 10 % intervals (table II). The amount of wind power in 2003 is close to the 20 % penetration case. Wind power predictions simulated with IMM model were used (Nielsen, 2002).

Three different transmission possibilities were assumed. In a theoretical "no transmission"–scenario, West Denmark was simulated without any exchange with neighbouring countries. In a "low transmission"–scenario, only Nordic connections to Norway and Sweden was assumed, a total of 1720 MW anticipated for year 2010. In a "high transmission"–scenario, possibilities to both Germany and Nordic countries (1200 MW + 1720 MW) were assumed.

As the exchange with Nordpool (Norway/Sweden) and Leipzig (Germany) is used according to prices at the markets, the low and high transmission scenarios were run with 2 price levels at the market. The average price was set to 220 DKK/MWh in the high price scenario and 120 DKK/MWh for Nordpool and 170 DKK/MWh for Leipzig in the low price scenario. Both the high and low price scenarios use approximate daily/weekly/seasonal profiles from the electricity markets.

In addition to the standard profiles for year 2010, one case was simulated taking real data from year 2001 as input profiles (8760 h) for market prices, electric demand and wind power. The price level in 2001 was on the average 177 DKK/MWh for Nordpool West Denmark area and 179 DKK/MWh at Leipzig.

Same set of events for thermal power plant outages was used in all simulated cases, so that the timing of forced outages would not influence the comparison of the cases. Spinning reserve requirement was set to 5 % of hourly load.

III. Simulation Results

Simulations with increasing amounts of wind power in the system have been conducted. Comparisons with the base case of no wind power installed have been made, to see the changes in thermal efficiency and costs, amounts of start/stops, regulation, exchange, discarded energy and emissions.

A. *Increased exchange with neighbouring areas*

The possibility of transmission between the neighbouring areas results in different base case situations for Denmark. There will be net exports from Denmark at high price level at the market, and net imports when low price at the market. Denmark is situated in between two different electricity market areas. This results in transit through the country, especially in exceptional hydropower situations when the market prices in the Nordel area differ notably from those of Germany. Only net exports are shown in Fig. 1. For high transmission cases there is a high level of exchange, starting at 14 TWh imports / 7 TWh exports for low price case and 11 TWh exports / 9 TWh imports in high price case.

Adding wind power will increase the exports and decrease the imports. When transmission to Germany is available, this will increase both the imports and exports, as there will be transit through Denmark from Nordic countries to Germany and vice versa. For high price cases adding transmission will not result in more net exchange for Denmark, only increasing transit. Comparison with the cases using real price profiles from 2001 shows that this is really what happens in high price years, adding of the transmission capacity does not alter the net exchange. For the low price situation, net exchange is even lower when adding transmission, compared with transmission only with Nordel. This can be explained by increased transit of cheaper Nordpool electricity to Germany.

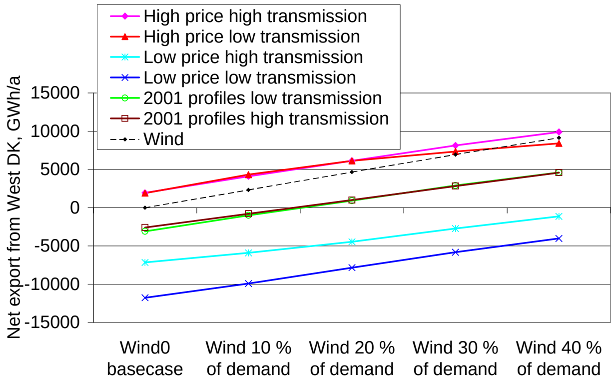

Fig. 1. Simulation results for net exports from West Denmark, when adding wind power to the system. Wind power added is shown as a dotted line.

Also wind power added to the system is shown in Fig.1. It can be seen that as wind energy is increased so is the net export. The major part of wind energy will flow abroad, even if the increase in net exchange is at a somewhat lower rate as the addition of wind power.

At 10 % penetration of wind, 80–90 % of the wind energy is exported in the various cases. The only exception is the case of low price - high transmission, where half of the wind power stays in West Denmark.

At 40 % penetration of wind 70–80 % is exported in the various cases. The only exception is the case of high price - low transmission, where most of the wind energy stays in West Denmark, as can be seen in the Fig 1.

B. *Effect on thermal system efficiency*

The simulation results include thermal power and heat production as well as the total fuel consumption. The total efficiency of the system can be calculated from these. Adding wind power will decrease the electricity produced by thermal plants. In the case of West Denmark thermal CHP system, this will actually result in slightly increased total fuel efficiency, by 0.1…1 % percentage point per 10 % wind power penetration added.

The explanation for this increase in the total efficiency of the thermal system comes from the combined heat and power production. CHP has a higher efficiency than producing only electricity (condensing power plant operation). The efficiency depends on the ratio of heat and power produced as well as the power plant characteristics. The heat demand and production is similar in all scenarios, as heat demand must be met locally, so the change in efficiency is due to different amount of electricity produced by thermal power production. For the base case high price - high transmission, the electricity produced in West Denmark is 25 TWh, and for the low transmission low price it is 11 TWh. The total efficiency varies between 70 % and 81 % respectively. When lower amount of electricity is produced, there is higher efficiency in combined heat and power production.

One effect from the fluctuating wind power is increasing the starts and stops of the thermal plants (Fig.2). The increase can actually only be seen directly when looking at the system without transmission possibilities.

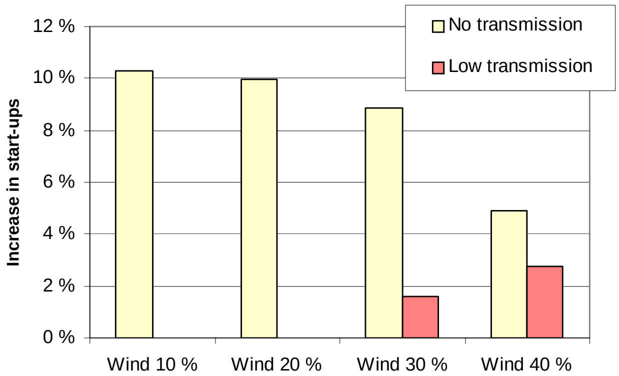

Fig.2. Simulation results for increase in total amount of start-ups in the thermal power plants, when adding wind power to the system.

The costs related to increased start-ups are seen in Fig.3. Allocating the extra start/stop costs to wind power added to the system, the cost for the first 10 % of wind power is 4.6 DKK/MWh and for the first 20 % of wind power 3.5 DKK/MWh. Having more than 20 % of wind power in the system means increased part load operation of thermal plants, and thus the starts and stops will be reduced. This extra cost will be seen as the increase in total costs of thermal power.

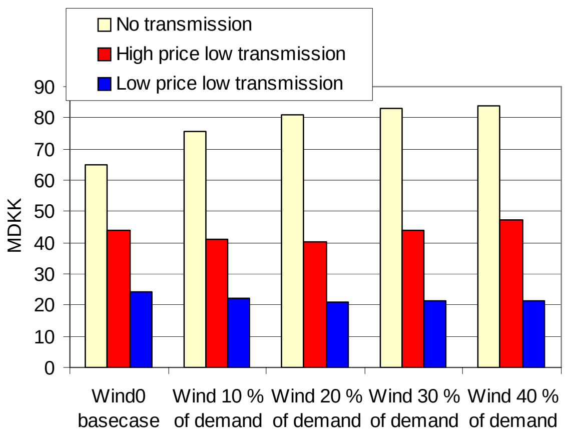

Fig. 3. Simulation results for start/stop costs from West Denmark, when adding wind power to the system.

For the cases with exchange, there is hardly any effect on the start up costs. The exchange is used to smooth out the variations, so that the start and stop cycles of thermal plants are not very much affected by wind power. Only low transmission cases are shown in Figs. 2 and 3 – the high transmission cases do not show any different behaviour. The level of the costs is 45 and 30 MDKK for high and low price, respectively, and increasing the wind power level does not make any significant trend in the costs.

C. Effect on thermal system costs

Wind power will replace electricity production from other sources, thus reducing the fuel costs. This reduction in fuel costs, allocated to the wind energy increased, will give the value of wind power to the system. In this value, also the difference in costs related to starts and stops, as well as maintenance costs have been taken into account (Fig. 4).

The total (operating) cost per MWh to the system is at the level of 230 DKK/MWh for the base case no transmission. Adding wind power increases the total costs by 15 % in the case of 40 % penetration. For other base cases, excluding costs from market exchange, the average thermal production costs in West Denmark range from 220 to 300 DKK/MWh depending on the level of production and net exports. Adding wind power increases the total costs by 4–5 %, except for the high transmission cases, where there is either not much increase (at high price level) or higher increase of 9 % (at low price level). As the wind power penetration gets higher, there will be increased cost per produced MWh for the thermal system, and thus reduced value of wind power.

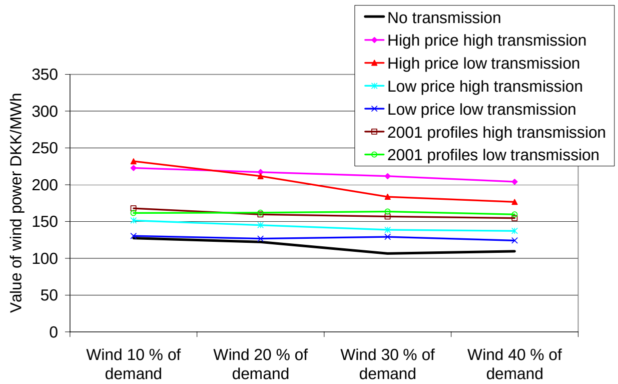

Fig. 4. Simulation results for reduction of costs due to added wind power: value of wind power to the system.

The value of wind power for West Denmark when operating without exchange is about 140 DKK/MWh, decreasing to 110 DKK/MWh at high penetrations. The value of wind power is higher when the price level at the market is higher, because then also wind power will get higher price at the market, and more expensive capacity will be operating for the wind power to replace in West Denmark. When the price level at the market is high the value is 220…200 DKK/MWh and when the price level is low, the value is 150…140 DKK/MWh. These are the results for high transmission capacity. When the transmission capacity is limited, the value of wind is somewhat higher.

At first the value of wind power is slightly higher than the market price, but it will drop as the penetration level increases. The market prices used with standard profiles do not reflect the influence of wind power production to the price level. The profiles and prices for year 2001 have this impact implicitly included, as there was already a substantial penetration level of wind power in West Denmark. This explains why the 2001 profile simulations result in value of wind power slightly lower than average market price.

D. Discarded energy

For the purely theoretical assumption of no transmission possibilities, Eltra system as described to the model for year 2010 would not operate reliably without wind, as there would be occasions of power lacking. In this case, wind power added would actually help the situation until 10 % penetration: even if surplus production occurs, it is less than the original lack of power. Significant amounts of critical, non exportable surplus power start to occur at 20 % penetration and this will increase more than linearly, reaching 1.5 TWh at 40 % penetration.

If there is low transmission assumed (only Nordel), the problem with surplus production will start when wind power penetration is more than 20 %, or, if the price at the market is low, only after 30 % penetration. The amounts are not very high: less than 0.2 TWh at 40 % penetration.

If there is high transmission assumed, both Nordel and Germany anticipated capacity in 2010, the surplus problem first arises at 50 % penetration.

E. Regulation due to wind power

Increased regulation due to wind power is an issue for all operating time scales of the power system. For the second/minute time scales of frequency reserves, this cannot be directly simulated by an hourly simulation model like SIVAEL. The effect of reserves, both spinning and load following, are taken into account by addressing the amount of 5 % of hourly demand to part load operation of power plants, as a requirement for reserves.

For the 15-minute to hour time scale of load following, the effect of prediction errors can be simulated, and the latest version of SIVAEL can take this into account for wind power. The model will allocate this extra regulation to either the central power plants, or to exchange with neighbouring countries. If these options are fully consumed, then the regulation is increasing the surplus or lack of power to the specific hour.

The prediction error comes from a stochastic simulation. The total prediction error for the year, as % of total wind power production, is 20 % in these simulations. This is lower than the state-of-the art for 12–36 hours-ahead errors for Denmark, but actually represents the current prediction error for up to 6 hours ahead. This is more relevant for the thermal power plant scheduling, if not quite in line with the day ahead spot market operation today.

It is worth noting that the amount of regulation due to wind power comes directly from the simulated prediction errors for wind power only. So the increase in regulation due to wind has been this 20 % of the wind power production in all the simulations.

When simulating the West Denmark area without exchange, the extra regulation need due to wind power is taken from the primary, central power units to the extent possible. For the first 10 % of wind energy, 20 % of the down-regulation needs result in surplus energy and 10 % of the up-regulation needs result in lack of energy. These situations will increase as wind power penetration increases, so that for 40 % penetration the thermal power plants will be able to provide only a half of the energy needed for regulation.

When simulating with exchange possibilities, the thermal power plants in West Denmark are used for about half of the up-regulation and only about 10 % of the down-regulation needs, the rest is from the exchange. This is the situation for 10 % wind power penetration: when increasing the penetration level, more exchange is used for up-regulation and less for down-regulation.

For low transmission cases the error in wind prediction will increase critical surplus situations, after 20 and 30 % penetration as described before in section D.

In the simulations, only the centrally operated power plants are involved in load following regulation. The prioritised, smaller scale CHP plants could also provide this service. Some estimated have been made (Pedersen & Eriksen, 2003), that suggest this could have an important value for the handling of prediction errors in West Denmark.

F. Effect on CO_2 emissions

When wind power is replacing electricity production and fuels for conventional fossil-fuelled power plants, there will be a reduction of emissions.

The only straightforward results for CO_2 effect of wind come from no transmission -scenarios, where all wind power will be replaced inside West Denmark. For the total fuel consumption in base case coal presents roughly half, gas a third, renewables (waste, straw, wood chips) 10 % and oil 2 %. Wind power will decrease mostly coal and gas, but at high penetrations also effects on renewables can be seen, and the low oil part will actually increase some. The first 10 % share of wind power will reduce 450 g CO_2 per each kWh produced. A 10 % increase from 30 to 40 % penetration level will result in lower abatement: 350 gCO2/kWh.

When transmission possibility is included, but the reduction of fuel use is calculated from only West Denmark, the reduced emissions from thermal production versus the wind power added will give modest values (50…200 g/kWh). This is due to the added exports. When addressing a value of 700 g/kWh to the increased net export amount (Holttinen and Tuhkanen, 2003), this gives a result of 600...700 g/kWh for the CO_2 abatement of wind power in Denmark.

IV. DISCUSSION

It is not straightforward to model wind power production with the existing scheduling models, as explained in Dragoon & Milligan, 2003. There are problems relating to the modelling of large-scale wind power: the hourly variations and prediction errors of wind power should be representative of large scale wind power with geographical smoothing in the production patterns. The uncertainties should be modelled for different time scales of unit commitment (starting and shutting down slow thermal units) and dispatch (production levels of thermal units). Problems can also emerge from the simulation logic in itself: optimisation of the system can be fundamentally different if taking into account the different nature of wind power production. Also regulation requirements are often not modelled directly, but coming from years of operating experience, so the effect of wind power cannot be modelled either. Modelling of market interactions and price levels should also be looked at when simulating wind power in the system.

In these SIVAEL simulations presented here, wind power production has been modelled in detail, with also prediction errors. The data for actual production is representative for large scale wind power, as it is realised production of thousands of wind turbines in Denmark. However, the prediction errors are simulated, and that part could still be improved, especially concerning the time scales that are relevant for the unit commitment and dispatch. In these simulations there is an effort trying to look at different market price levels and situations (exchange possibilities). However, at large penetrations there will be influence of wind power on the market prices, and this has only partly been included when using the 2001 data for simulations. For the underlying logic in optimising, there is not wind power taken into account specifically, but this will be subject to changes in the next version of the model. When studying the effect of wind power on regulation, it has to be taken into account that the imbalance is dealt with on a control area basis. Every change in wind output does not need to matched one-for-one by a change in another generating unit moving in the opposite direction, but the aggregation must be balanced. Here only regulation due to wind power has been studied. For high penetrations in West Denmark, most of the imbalance comes from wind power. It would be interesting to see the effect when load forecast errors would be present in the simulations.

The results here are of a theoretical study, increasing wind power while keeping the rest of the system the same. With large increased capacity and production, this results in over capacity of production, when no other capacity is withdrawn. This can be one thing explaining the large increased net exports.

All in all, capturing the effects of wind power on a power system is not an easy task. The effects are spread over the total control area (synchronously operated area) or electricity market, with constraints on transmission capacities between the areas. Modelling a small part of the area has to take into account these transmission capacities, but as wind power in the neighbouring area is not modelled, the use of exchange can be overestimated in the simulations. Also there can be an effect on the available transmission capacity due to wind. Contingencies, due to dynamic phenomena, cannot be modelled with an hourly time scale model. Due to this, the low transmission possibility scenario is often used.

Comparison to results from other similar studies can be made in regard to discarded energy. Some studies have been made for thermal systems, taking wind power production in but leaving the thermal plants running at partial load even at high winds to provide regulation. The results are that at about 10 % (energy) penetration, the curtailment needs for wind power will start, and at about 20 % penetration discarded energy will become substantial, losing about 10 % of the total wind power produced (Giebel, 2001;CER/OFREG NI, 2003). This corresponds to the results presented here for the no transmission capacity case. For West Denmark, earlier simulations of the system resulted in significant discarded energy at high penetrations, when disregarding the transmission capacity to Germany: a 1.3 TWh critical surplus energy at 12 TWh wind power production, a 50 % penetration (Lund & Münster, 2003). This is a higher surplus than estimated here for the corresponding low transmission case (less than 0.2 TWh at 9.2 TWh production, a 40 % penetration). The reason is that here the CHP capacity that can be operated flexibly is higher. For the earlier results, it has been estimated that nearly 50 % wind power penetration could be accommodated with minor losses of discarded wind energy. This requires using the existing heat storage and boilers of CHP production units in collaboration of wind power, together with some flexible demand and electrical heating (Lund & Münster, 2003).

The CO_2 abatement of wind power in an area that is part of a larger system is especially difficult to catch. What production do the net exports really replace, when there is the low transmission scenarios with exchange only to hydro power dominated Nordel? Actually, this is a theoretical question as it is a theoretical case of only Nordel exchange, and in real life net exports would probably be to Germany and reduce their coal condense power production. When wind is replacing imports from Nordel on a wet, low price year, then either wind will actually have no CO_2 benefit, or the hydro power is just moved on to Germany.

The results from the different transmission scenarios show that there is not so much effect on the local system but to the exchange. This can be a real and valid result – even if wind power penetration level in West Denmark and North Germany is high, it is not high in all Central Europe system.

V. CONCLUSIONS

The impacts of large-scale wind power to a thermal system have been simulated for the West Denmark power system. The exchange to neighbouring countries has been part of the simulations, with different scenarios for transmission possibilities and prices at the market. Wind power was increased at 10 %

intervals, from 0 to 40 % of wind power penetration of gross demand (energy).

According to the simulations, wind power will increase the exports and decrease the imports to West Denmark. A major part of wind energy is exported to neighbouring countries. This effect will decrease as the penetration level of wind power increases.

There will be a slight increase in the total efficiency of all thermal combined heat and power plants in West Denmark as wind power is added to the system. This is due to better total efficiency for heat and power plants when operating in lower power to heat ratios.

The increase on total start and stop costs of the thermal power plants can only be seen when simulating the system without transmission possibilities. Allocating the extra start/stop costs to the amount of wind power added to the system, the extra cost for the first 10 % of wind power is 4.6 DKK/MWh and for the first 20 % of wind power 3.5 DKK/MWh. Having more than 20 % of wind power in the system means increased part load operation of thermal plants, and thus the starts and stops will be reduced.

Extra cost of part load operation is seen as the increase in total costs of thermal power. There will be reduced value of wind power and increased cost per produced MWh for the thermal system, as the wind power penetration gets higher. The value of wind power is higher when the price at the markets is higher. The value is nearly at the market price level for the first 10 % of wind power, reducing as penetration increases.

At high penetration levels, a part of the wind energy will have to be curtailed in order to maintain a reliable system operation. According to these simulations, critical non exportable surplus production would occur after 20 % penetration for low transmission possibilities.

The effect of wind power on CO_2 emissions in West Denmark are only seen when simulating the system without transmission possibilities. At 10 % wind power penetration wind power decreases the emissions at the rate of 450 gCO_2/kWh. A 10 % increase from 30 to 40 % penetration level will result in lower abatement: 350 gCO_2/kWh.

The simulations presented included prediction errors for the wind power production. The total amount of prediction error presented about 20 % of the wind energy produced. The model allocated the extra regulation due to prediction error to either increased part load operation of centralised thermal power plants or to exchange. According to the simulations, most of the down regulation and half of the up regulation was handled with changing exchange. Adding wind power would result in more thermal plants reacting for the down regulation, and less for up regulation. If no transmission was possible for the system, at 40 % penetration of wind power the thermal power plants would be able to provide only half of the energy needed for regulation.

Capturing the effects of wind power on a power system with simulation models is not straightforward. Most of the effects are dissipated to other parts of the power system than the area studied. This is quite possible for the foreseeable future, because even if there is already high penetration of wind power in Denmark and Northern Germany, it is still a minor part of the total Central Europe power system.

VI. References

CER/OFREG NI, 2003. Impacts of increased levels of wind penetration on the electricity systems of the republic of Ireland and Northern Ireland: Final report. A report commissioned by Commission for Energy Regulation in Republic of Ireland and OFREG Northern Ireland. Available at < http://www.cer.ie/cerdocs/cer03024.pdf>

Dragoon, K. & Milligan, M. 2003. Assessing wind integration costs with dispatch models: a case study. AWEA Windpower 2003 conference, May 2003, Austin, Texas. Available at http://www.nrel.gov/publications/

Eriksen, P B, Pedersen, J, Parbo, H, 2002. Challenges of Large-Scale Integration of Distributed Generation into Eltra's System. Proceedings of 2nd International Symposium on Distributed Generation: Power System and Market Aspects, Stockholm, 2–4 October 2002.

Holttinen, H. & Tuhkanen, S. 2003. The effect of wind power on CO_2 abatement in the Nordic countries. Energy Policy, 2003 (in print).

Lund, H. & Münster, E. 2003. Management of surplus electricity production from a fluctuating renewable energy source. Applied Energy 76 (2003) 65–74.

Nielsen, H. A. 2002. Analysis and simulation of prediction errors for wind power productions reported to Nordpool. IMM, Technical University of Denmark, 2002 (In Danish).

Pedersen, J. 1990. Sivael – Simulation program for combined heat and power production. Proceedings of International conference on application of power production simulation. Washington, 1990.

Pedersen, J. & Eriksen, P. B. 2003. Simulation model including stochastic behaviour of wind. Proceedings of Fourth International Workshop on Large-scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, 20–21 October 2003, Billund, Denmark.