VTT WORKING PAPERS 122

Bettina Lemström, Juha Kiviluoma, Hannele Holttinen
& Lasse Peltonen

Impact of wind power on regional power balance and transfer

ISBN 978-951-38-7183-3 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1459-7683 (URL: http://www.vtt.fi/publications/index.jsp)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT, Vuorimiehentie 5, PL 1000, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 7001

VTT, Bergsmansvägen 5, PB 1000, 02044 VTT
tel. växel 020 722 111, fax 020 722 7001

VTT Technical Research Centre of Finland, Vuorimiehentie 5, P.O. Box 1000, FI-02044 VTT, Finland
phone internat. +358 20 722 111, fax +358 20 722 7001

Cover photo: Oulunsalo wind power plant, Lentokuva Vallas Oy

Technical editing Leena Ukskoski

Series title, number and
report code of publication

VTT Working Papers 122
VTT-WORK-122

Author(s)
Bettina Lemström, Juha Kiviluoma, Hannele Holttinen & Lasse Peltonen

Title

Impact of wind power on regional power balance and transfer

Abstract

This report describes a method on how to analyse wind power influence on power transfer between different areas in a power system. It discusses how different aspects can be modelled and taken into account. Hourly consumption as well as conventional and wind power generation has to be predicted and modelled for each area for the whole period in question.

In order to study the power transmission between the areas in a meshed system the influence of a given generation or load change on a given line flow should be studied by power flow calculation. In this report, an approximate method that can be used if the system can be reduced to a non-meshed or radial form is presented. The method is illustrated by fictitious examples of 0 MW, 2000 MW and 4000 MW of wind power installed in Finland. In order to get the generation units dispatched according to marginal costs, the market model Wilmar is used. The period of analysis is one year and the time step one hour. The impact of wind power on the power balance, power flow between the areas and congestion is calculated and analysed for the example cases. The main results from the calculated cases regarding transmission in Finland are that transmission across cut A (South Finland) is not congested, but a new transmission line over cut B (Middle part of Finland) might be economic in the wind scenarios due to increased transmission and congestions. Regarding the transmission between Finland and Sweden it was found out that situations with simultaneously high wind power production and high import will be rare as wind power will replace import to a large extent. Gererally, the more wind power there is in Finland:

- the more often is cut B congested
- the more power is exported to Sweden over the AC-connection
- the more often is Finland exporting power to Sweden.

ISBN
978-951-38-7183-3 (URL: http://www.vtt.fi/publications/index.jsp)

Series title and ISSN
VTT Working Papers
1459-7683 (URL: http://www.vtt.fi/publications/index.jsp)

Project number
34492

Date
June 2009

Language
English

Pages
43 p.

Name of project
Tuulivoiman järjestelmävaikutusten arviointi

Commissioned by
Tekes

Keywords
wind power, transmission, bottlenecks, congestions

Publisher
VTT Technical Research Centre of Finland
P.O. Box 1000, FI-02044 VTT, Finland
Phone internat. +358 20 722 4520
Fax +358 20 722 4374

Preface

The work presented in this report is a part of the Finnish national project of Task 25 of the Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Energy Systems of the International Energy Agency. Task 25, *Design and Operation of power Systems with Large Amounts of Wind Power*, is an international research cooperation started in 2006 and coordinated by VTT.

The authors with to thank Fingrid for giving insight into dividing Finland into areas and the current transmission limits between the areas, used in the case study calculations.

The authors would like to express their gratitude also to Tekes, the Finnish Funding Agency for Technology and Innovation for financing this research work.

Contents

1. Introduction

Wind power is today in many countries the power generation form that increases most. Some geographical areas have better wind resources and are better suitable for wind power than others. Consequently wind farms are concentrated to these areas. From a power system point of view wind farm locations are, unfortunately, often far from load centres and therefore the power has to be transferred over some distance to the main grid and further to electricity end-users.

Large scale wind power generation increases the total power generation in some parts of the power system while generation in other parts decreases. This affects directly the power flow between areas and may cause congestion in the transmission system, require grid reinforcement or changes in the operation of the power system.

This report describes a method on how to analyse wind power influence on power transfer between areas. It discusses how different aspects can be modelled and taken into account. When looking at a power system situation far in the future, the analysing approach should not be too detailed and case-sensitive. On the other hand much data is needed and many assumptions have to be made. The method is illustrated by fictitious examples with 2000 MW and 4000 MW of wind power installed in Finland in 2015. The period of analysis in the example is one year and the time step one hour.

2. Method and data

The problem at hand would be best solved if one was able to solve power flow and dispatch optimatization simultaneously. Unfortunately there seems to be no model commercially or publicly yet available that could handle this in a system with combined heat and power production and reservoir hydro power. Therefore, we have used a dispatch model with transmission limits over most likely constrained cuts in the system. The power system was reduced to radial form in a way that was considered to give most reliable results. The purpose was to get results on how much and how often the capacity constraints over the defined cuts are exceeded.

Since the objective of the study was not to plan the location and the size of possible new transmission lines, it was decided that setting up a power flow model to check the results would have been too much work at this point. Results would be more robust if power flow model had been used.

2.1 Areas

The power system that is studied should be divided into areas based on the grid infrastructure. The areas are to be defined so that potential grid congestion would occur mostly *between* the areas, not *within* the areas. Finland, our example country, is divided into eight areas, see Figure 1. In addition there are five interconnections abroad. Three of these are to the same electricity market area, i.e. one to Norway and two to Sweden. The connections to Estonia and Russia are DC-links as is the Southern link to Sweden.

As one can see from Figure 1 the areas form a meshed system. In order to study the power transmission between the areas in a meshed system the influence of a given generation or load change on a given line flow should be studied by power flow calculation. If one does not have, or does not wish to use, a grid model with impedances or power transfer distribution factors for the modelled system, the system has to be reduced to a non-meshed or radial form. When no parallel and diagonal routes for the power flow exist in the model the flows can be solved simply by addition and subtraction of domestic generation and consumption and cross-border-flows.

In this work the simple approach without power flow calculation is used. There are several ways to reduce the system in Figure 2. Most logical with respect to wind power location and grid constraints is to aggregate areas 3 and 4 into one region and 5, 6 and 7 into another. Also the alternative with areas 3, 4 and 5 forming one region and 6 and 7 another is sensible, see Figure 2. The Åland islands in South-West are normally fed from Sweden and are thus not included in this study.

When the areas are defined, one has to predict and model hourly consumption, conventional generation and wind power production for each of the areas for the whole year in question.

The analyses can include several different scenarios with regard to wind power location and amounts, electricity consumption level, import/export assumptions, transmission capacity between areas etc.

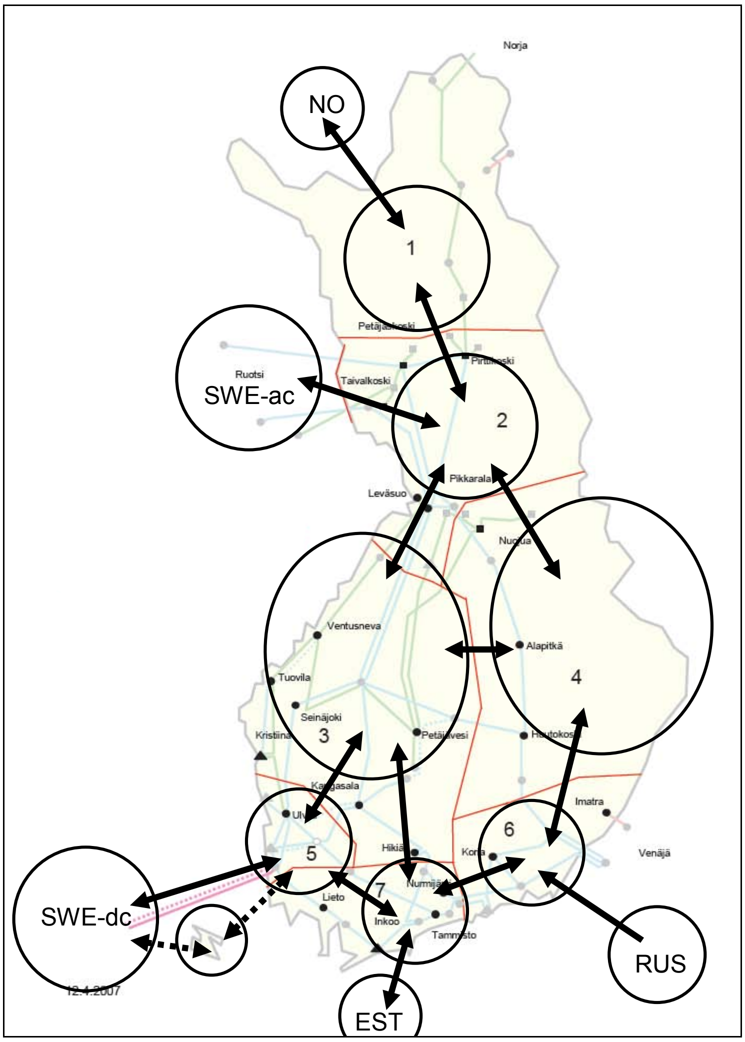


Figure 1. Division into areas. Geographical areas are shown with red lines. Power transfer between areas is shown with black arrows.

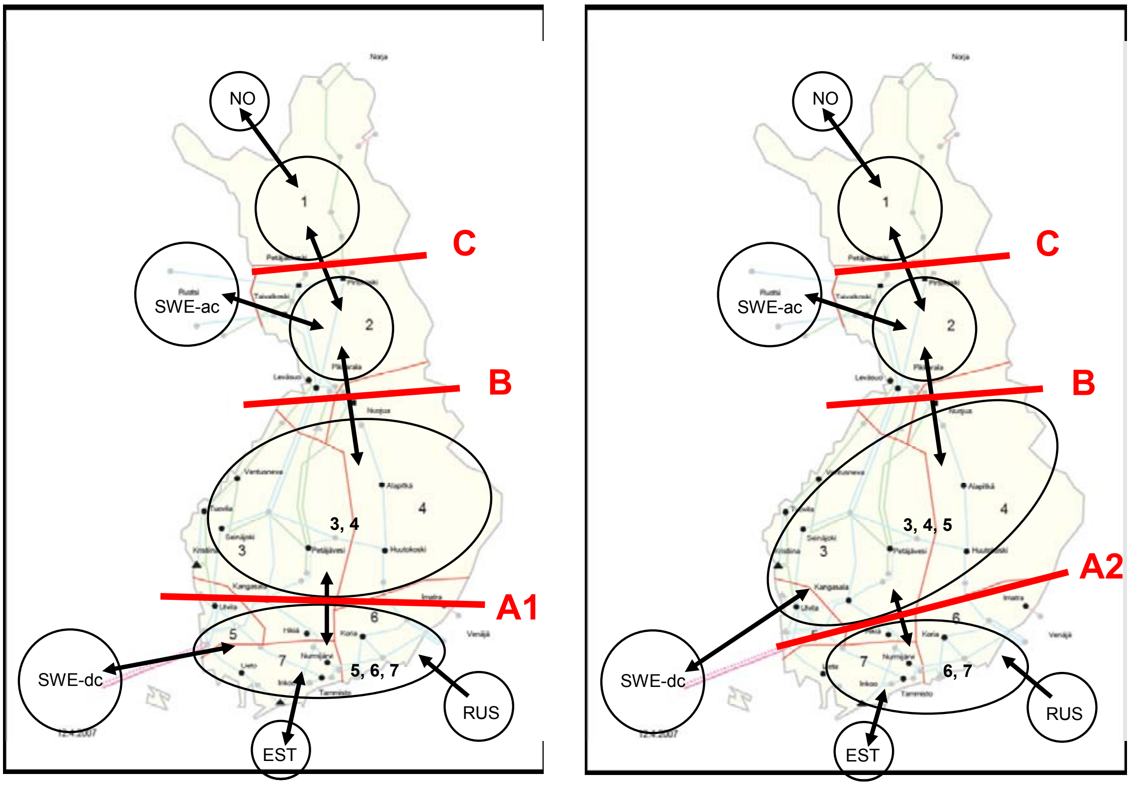


Figure 2. Two ways of grouping the areas into non-meshed regions.

2.2 Wind power

2.2.1 Finland

Available information on wind power production in each area is required. As future scenarios of wind power are studied, there is often lack of wind power production time series that could be used directly. This means that the time series of wind power production have to be generated in one way or another, from existing data of wind farms and wind speed measurements.

Synchronous data with load is necessary especially if the wind and load experience or are expected to experience some correlation. This is why data based on same calendar years often is used when producing the time series.

It should be kept in mind that large scale wind power usually means there is considerable smoothing effect for production from several sites and hundreds if not thousands of turbines. Up-scaling data from too few measurement points will result in wind power time series that exaggerate the variability of wind power. The variability can be checked with data from real large scale power production, for example Denmark and Germany [1].

To make a sensitivity analysis, different wind resource years should be used. In this study only one year was analysed: 2005. It was a relatively windy year. Data for 2006 was also prepared, but the model runs were not carried out due to time constraints.

For the example case wind power time series were constructed from hourly power production measurements from existing wind farms. Two year time series (2005–2006) was acquired from 83 wind turbines (total capacity of 81 MW), grouped into 21 time series. Additionally two wind speed data time series from 100 m masts were used to complement the data. They were converted to 2 MW turbine power output using a smoothed out power curve to make the point-wise measurement to represent a wind farm. The sites for data are presented in Figure 3. The Åland (Ahvenanmaa) time series were used to represent wind power production in the Turku region (area 7) – the Åland area as such was excluded from this study as it is mainly fed from Sweden. The Raahe time series were used to regional time series of both areas 2 and 3 as the site lies on the border of the two areas.

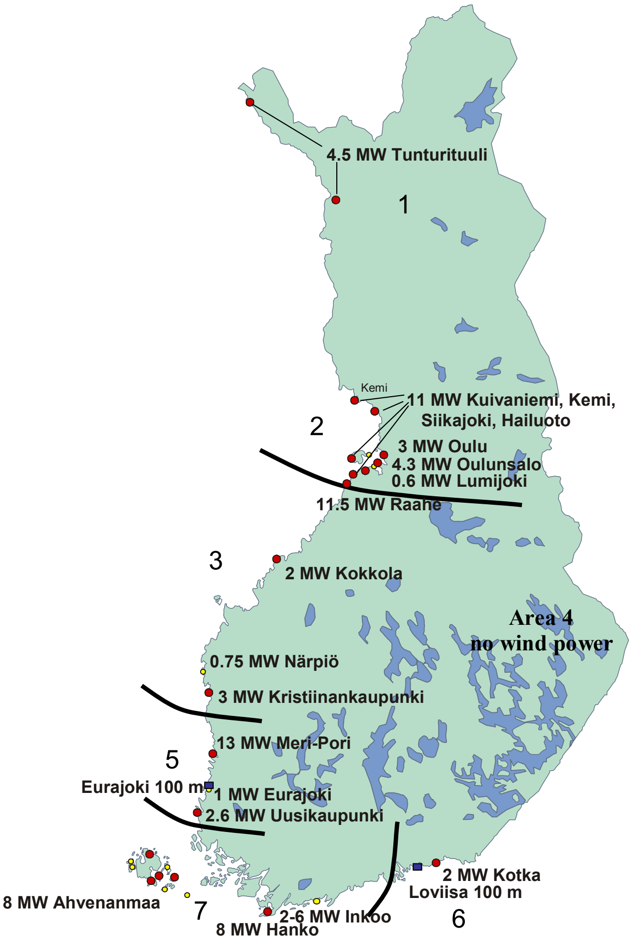


Figure 3. Data sites for the hourly time series acquired for the regional wind power production. Single turbines are shown with smaller dots, wind speed measurements with square marks. The texts show grouping of original data.

The time series were converted to relative time series as % of installed capacity. In this process the data was cleaned of periods of zero power production due to technical unavailability of turbines. Finally, the time series were grouped to regional power production time series. Most of the production time series were up-scaled during this process, as the future 2000–4000 MW wind power capacity would include a large share of offshore, better wind resource sites. As some data was seen to be less representative this was taken into account by giving a lower weight in the averaging process.

Lapland (area 1) and the Eastern part of South coast (area 6) have data from only two sites each. However, these areas also have the least wind power projected in the scenarios used.

It has been assumed that when summing up the original time series from sites several hundred kilometres apart the smoothing effect would be sufficiently taken into account. Checking this assumption on the variability of hourly production showed that there is somewhat more variability in the time series than would be expected. The standard deviation of hourly variations -time series for Finland should be about or even below 3% of installed capacity (for Denmark, 3–4%) [1]. In these time series the values for standard deviation was more than 4%. These time series thus represent a conservative assumption in regarding hourly variability.

The wind power scenario for 2000 MW and 4000 MW wind power in Finland is presented in Table 1. An example of the 4000 MW time series for two weeks in January 2005 is presented in Figure 4.

Table 1. Installed capacity and yearly production in total and divided into areas in the 2000 MW and 4000 MW wind power cases. Average power is relative to installed capacity. Area 4 inland was assumed to have no significant wind power installed.

	Area 1	**Area 2**	**Area 3**	**Area 5**	**Area 6**	**Area 7**	**Total**
Case 2000 MW Installed capacity (MW)	100	900	400	300	100	200	**2000**
Yearly production (TWh)	0.29	2.42	1.07	0.79	0.54	0.26	**5.38**
Case 4000 MW Installed capacity (MW)	200	1800	800	600	200	400	**4000**
Yearly production (TWh)	0.58	4.85	2.15	1.59	1.07	0.52	**10.76**
Average power (% of installed)	33.2%	30.7%	30.6%	30.2%	29.4%	30.6%	**30.7%**

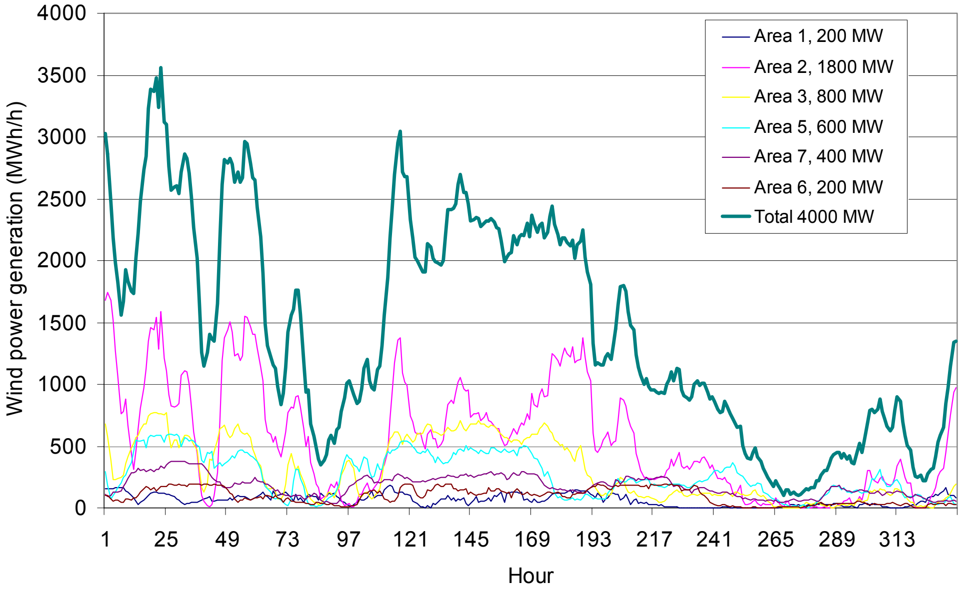


Figure 4. Example of hourly wind power data in the 4000 MW case – two weeks in January, 2005.

2.2.2 Sweden, Norway and Denmark

Wind power production in Sweden by 2015 was assumed to raise to 7.0 TWh/a in Sweden and 5.0 TWh/a in Norway. Current levels are much lower. In Denmark production is assumed to raise less, up to 9.9 TWh/a. Hourly wind power production time series for Sweden, Norway, and Denmark have been made using data from NCAR/NCEP ReAnalysis data. Sigma layer 995 was used as the source for data and it was scaled to a representative capacity factor using wind speed profile based on measurements in Pori. It was assumed that on average turbines will have larger diameter compared to generator size than nowadays and that their hub height will be higher – both of which will raise the average capacity factor. (Table 2)

Table 2. Wind power data in other Nordic countries as input for the simulations.

Region	**Wind power capacity (MW)**	**Wind power production (TWh)**
Denmark East	831	1975
Denmark West	2576	7924
Norway Middle	361	1170
Norway North	698	2321
Norway South	433	1499
Sweden Middle	506	1333
Sweden North	1131	3055
Sweden South	863	2608

2.3 Load

2.3.1 Finland

Consumption time series can be predicted and generated in different ways depending on what data is available. Our example case includes two methods: one simple for the neighbouring countries and one more detailed for the country under study.

In the simple method historical consumption series are scaled up to match the predicted yearly energy consumption. If the hourly consumption profile is not known, some other method, than scaling historical data is needed. This is the case for the individual areas of Finland. Hourly consumption time series are therefore created for each area on the basis of:

- estimates of the yearly electricity consumption for the different consumer sectors in that particular area
- consumption indexes based on measurements at customer sites
- area specific monthly average outdoor temperature.

The consumption indexes used in the example origin from long time load research and are based on more than 1000 consumer load recordings. The load research was conducted by the Association of Finnish Electric Utilities from 1983 to 1994, and since then at VTT's responsibility [2].

The consumption index system consists of two index series for each customer type. The seasonal index describes the power level in two-week-periods and consists hence of 26 values. The day indexes describe the hourly consumption for three types of days: weekdays, Saturdays and Sundays. Each two-week-period has its own day indexes, i.e. 3 x 24 values. Holidays and eves are modelled as Sundays and Saturdays respectively. As an example the indexes for four types of dwelling are shown in Figure 5 (seasonal indexes) and Figure 6 (day indexes from the first two-week-period).

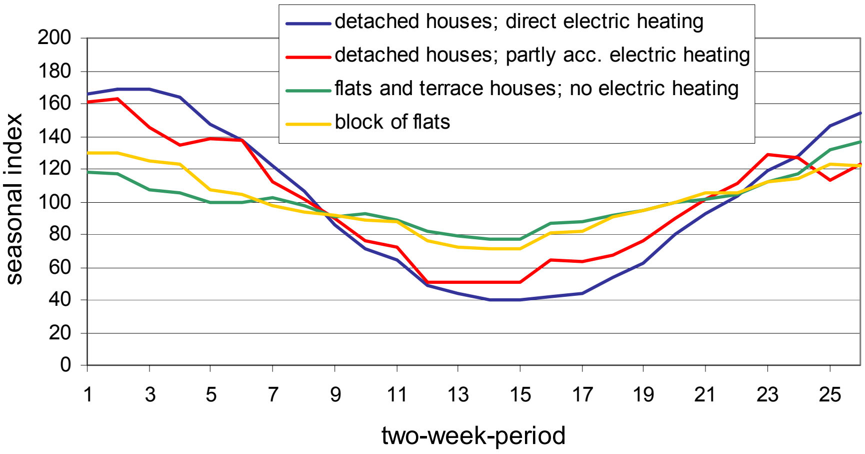


Figure 5. Seasonal indexes for four types of dwellings.

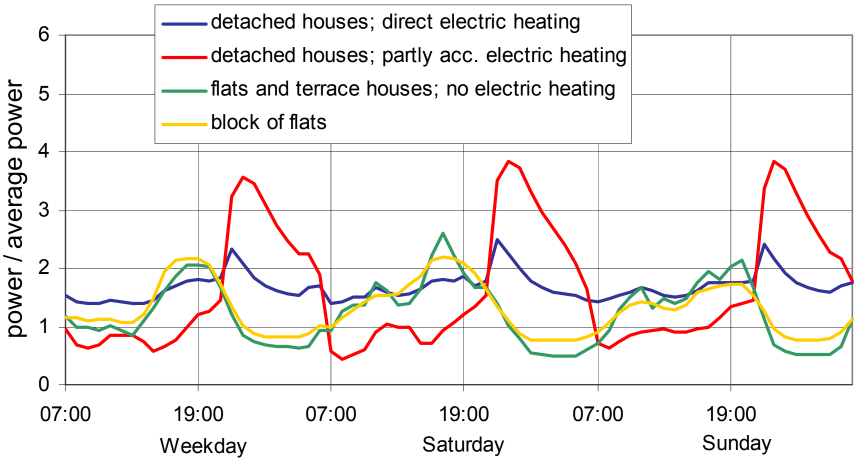


Figure 6. Day indexes for four types of dwellings.

The outdoor temperature impacts significantly the power consumption of electric heating load. 1 ºC change in outdoor temperature makes on average a 4% change in the power consumption. This can be included in the consumption index method for customer types with direct or accumulating electric heating.

The type and number of consumers differ considerably from one area to another. This has been taken care of in the Finnish example case by using regional or municipality level data on:

- yearly consumption of five sectors (dwellings, agriculture, industry, private and public service)
- heating system, number and surface of buildings, number of inhabitants per house type (block of flats, terrace house, detached house)

- number of farms per farm type (dairy farm, ranch etc)
- number of business places, energy consumption by branch of industry (food, textile, timber, paper, chemical, metal industry).

Private and public service is assumed to have same composition despite municipality and area. This means that the energy consumption in the private service sector is divided similarly in each area on stores, restaurants, hotels etc. The same applies for public service consumption in schools, health care, administration, sport and cultural facilities etc.

In the example case presented in this report consumption indexes of altogether 25 customer types are used. Different monthly mean outdoor temperatures are used for the areas as the areas are geographically widely spread out and face different weather conditions (Figure 8). For simplicity and availability reasons local long term average temperatures are used. The method could be improved by modifying the computer code to utilize daily temperatures. Intra-day temperatures are not suitable because the consumption indexes already include day-night variation as they are based on real load measurements. By using daily temperature data from the same year as the wind data possible correlation between wind and outdoor temperature would be taken into account correctly. Power losses of 3% are added to the consumption time series as a last step.

This fairly detailed method catches generally well the consumption variations. One uncertainty is, however, caused by the consumption indexes themselves as they are based on historical, not very recent data. Some small changes in electricity use and human behaviour can already today be noticed compared to last century: stores have longer opening hours and are often open on Sundays as well, people are later awake in the evenings, starting of warm water boilers is more irregular.

In the future increased use of electric vehicles and heat pumps is expected to change the consumption profile. Energy saving and flexible tariffs are other aspects that might have a noticeable influence. One can, however, assume that omitting these has only a minor, if any, impact on the results of this study. The same consumption time series are used for the cases with and without wind power, and the focus is on the impact of wind power on transmission, not on the consumption as such.

In the example case a total consumption of 100.5 TWh is assumed for Finland in year 2015. The consumption by sector is presented in Table 3 and Figure 7. For comparison the actual consumption for year 2000 is also shown. Housholds and industry are expected to increase their electricity use the most in the future, whereas the other sectors remain on the year 2000 level or increase only slightly. The areas have different consumer mix and consequently there are noticeable differencies in the seasonal variation of the consumption, see Figure 9. For instance the consumption varies less during the year in area 5 and 6 than in other areas.

Table 3. Consumption by sector 1) in Finland in year 2000 and 2) in the simulation scenario 2015.

	Actual		**Scenario**	
	2000		**2015**	
Household	16.5 TWh	21%	23.2 TWh	23%
Agriculture	2.4 TWh	3%	2.4 TWh	2%
Industry	43.6 TWh	55%	56.7 TWh	56%
Private service	9.0 TWh	11%	9.9 TWh	10%
Public service	4.9 TWh	6%	5.3 TWh	5%
Losses	3.0 TWh	4%	3.0 TWh	3%
Total	79.4 TWh	100%	100.5 TWh	100%

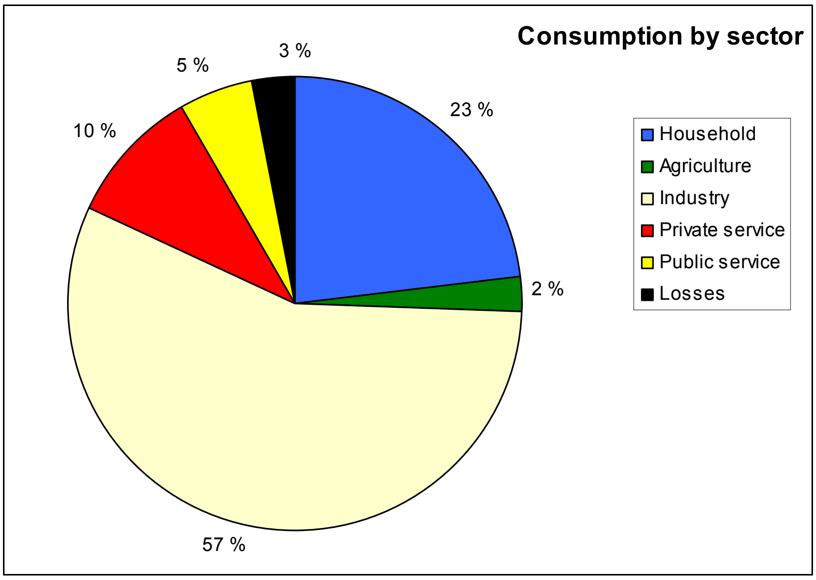


Figure 7. Consumption by sector in the scenario for 2015.

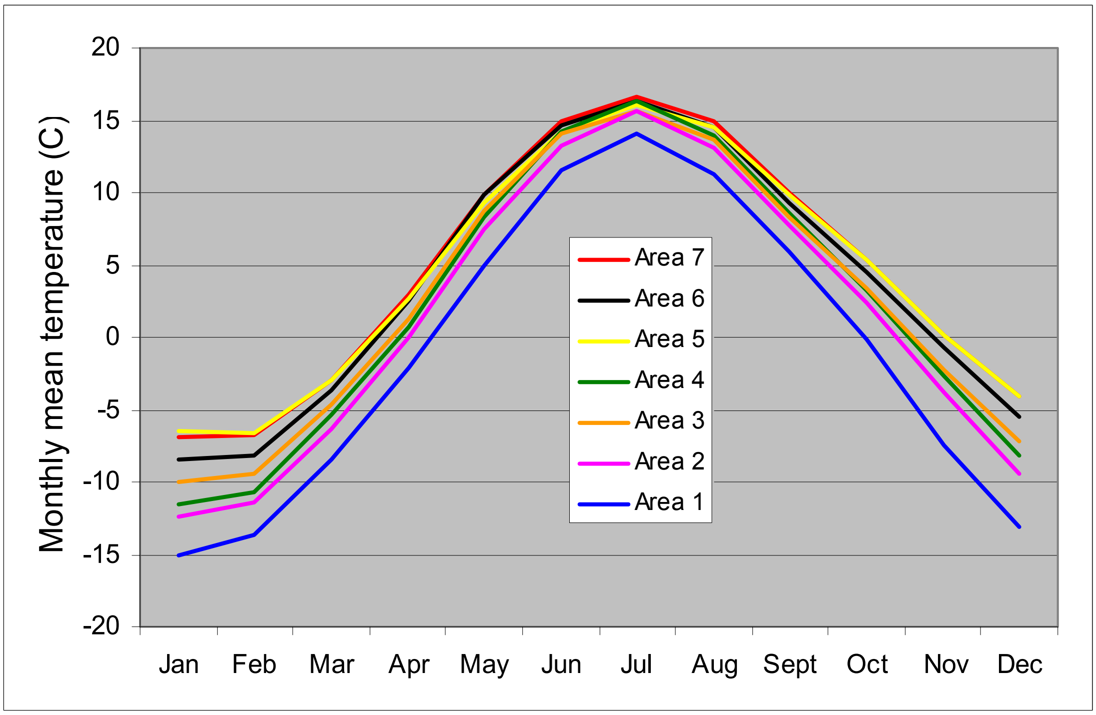


Figure 8. Monthly mean temperatures for the areas.

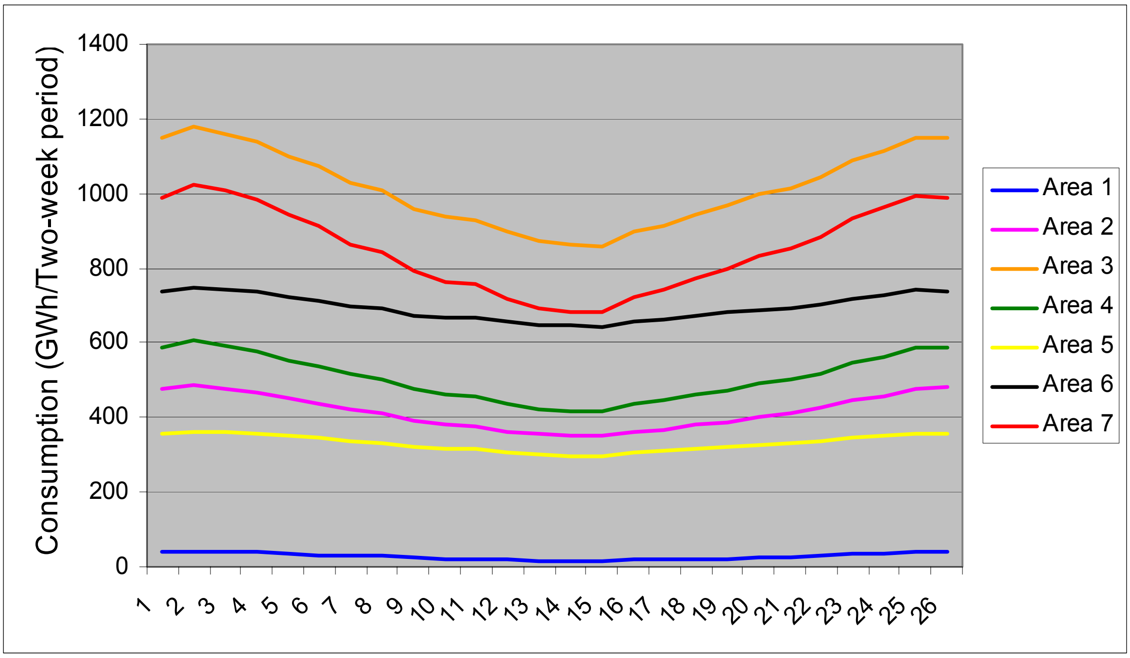


Figure 9. Consumption per two-week period.

2.3.2 Denmark, Norway and Sweden

For the neighbouring countries in the same market area, i.e. Denmark, Norway and Sweden, publicly available historical hourly consumption time series from 2005 were used (Table 4 and Figure 10).

Table 4. Annual consumption in the simulation scenario.

	Annual consumption (TWh)
Denmark West	21.2
Denmark East	14.3
Norway	121.3
Sweden	146.1

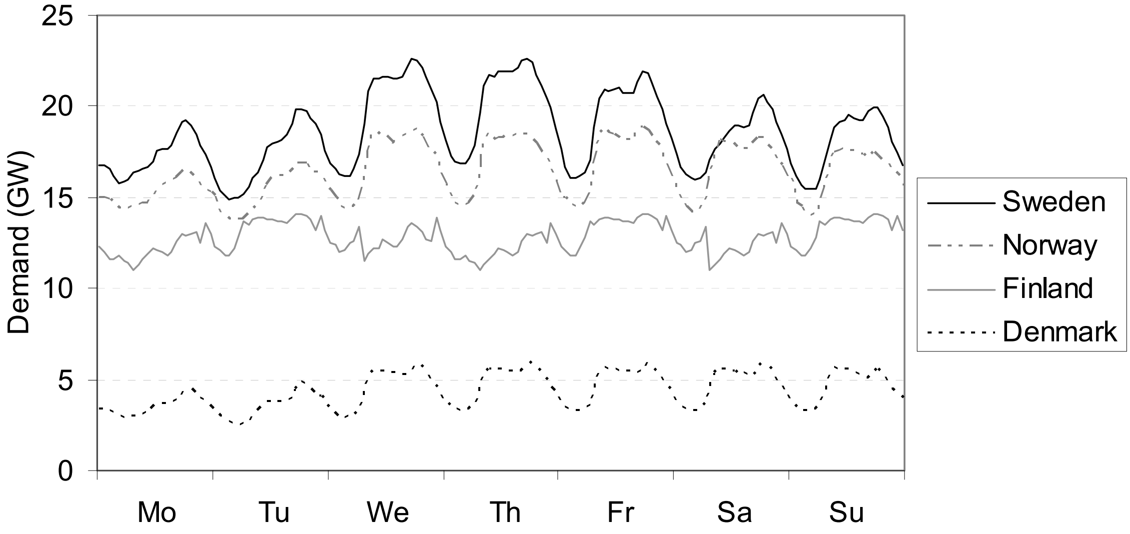


Figure 10. Electricity demand during the first week of January.

2.4 Other generation

In order to simulate dispatch of power plant according to marginal costs, a market model called Wilmar is used [4]. Wilmar optimises the use of power plants in the market area for each hour. It takes into account operation of CHP plants, wind power production, unregulated and regulated hydro power, as well as the need for reserves.

Without a market model, the analysis would be restricted to simple time series analysis and it would not capture dynamic nature of the power system. Once there is more wind power production in different areas in the system, power plants with highest marginal costs during a given hour will produce less. The congestion points will change accordingly and in some cases production might need to be curtailed due to congestion.

Wilmar emulates a zonal market system with a day-ahead and a regulation market. Regulation market offers a possibility to correct for prediction mistakes in the load and wind power production. This option was not used in this study, since it was considered not to be very important for a congestion study.

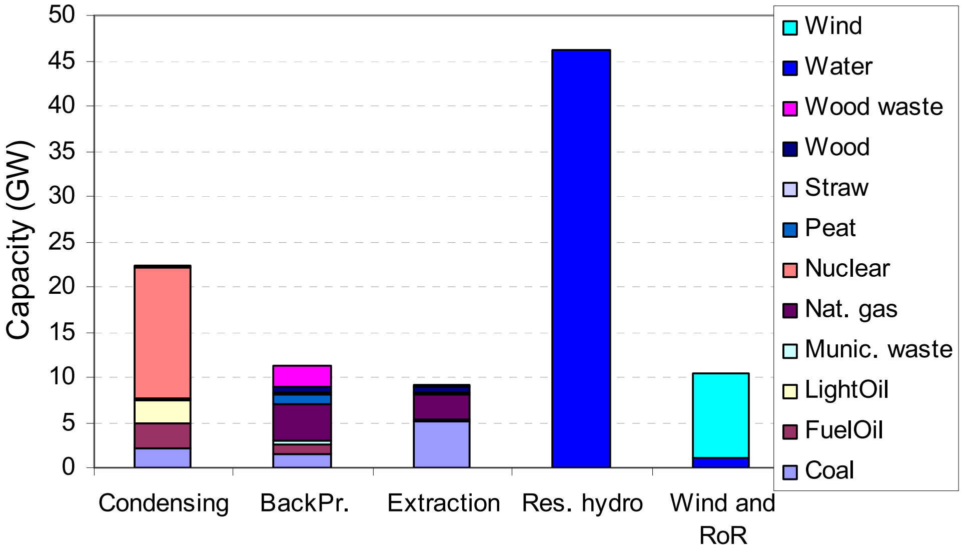
The zonal price areas are approximately the same as the Nordic market currently has with the exception of Finland. Finland forms one price area in the NordPool market. In practice internal transmission bottlenecks are handled by counter-trade when they are rare or small. More permanent bottlenecks have been removed by reinforcing the grid. In this analysis Finland was divided into more areas in order to see whether wind power would create enough congestion in predefined cuts to warrant new transmission lines. Importing and exporting power between price areas is restricted by a simple capacity limit. This is a modelling simplification replacing actual power flow analysis.

In case there is congestion between two areas, market prices between the areas will differ and the congestion can be priced. When there is a large need for extra transmission capacity, the price difference is bigger than in case of a small need for extra capacity. However, this gives only the *marginal* price for the congestion and serves best as an indicative measure of the severity of congestion. In practice the benefit from new transmission capacity will decrease with increasing new capacity. Therefore, we analyse in addition cases with and without a transmission expansion with a capacity equalling a new line in the most important cuts. Comparison of the operational costs of the power system between these two cases yields an estimate on the value of the transmission capacity addition.

In the simulations Finland was further divided into over one hundred district heating areas. Each of these had to be served by local heat production, which usually had an option to use CHP plants or heat boilers. Most CHP plants are backpressure plants with fixed ratio between heat and power production. This, combined with lumpy unit commitment decisions, creates lot of restrictions on the power plant dispatch decisions. This is somewhat relieved by relatively flexible reservoir hydro power.

Consumption time series as described in the previous chapter were used as input data for the model. Power plants included in the model were current plants plus forecasted additions minus forecasted retirements by 2015 (Figure 11). To get realistic results it is important to have a reliable set of power plants, since transmission will be heavily influenced by the location and production of the power plants.

Another aspect, which has to be representative, is the relative order of marginal costs of different power plants (Figure 12). If they are wrong, wrong power plants will be used in the margin, production might be in the wrong zone and transmission congestion results will be misleading. In addition some future marginal costs are not known very well. Especially fuel costs can change and this introduces an additional layer of stochasticity into the analysis. In a more comprehensive study, the results should include sensitivity analysis on fuel prices and other variable costs like CO_2 price.



Kuva 11. Power capacity divided into different power plant categories for the Nordic system.

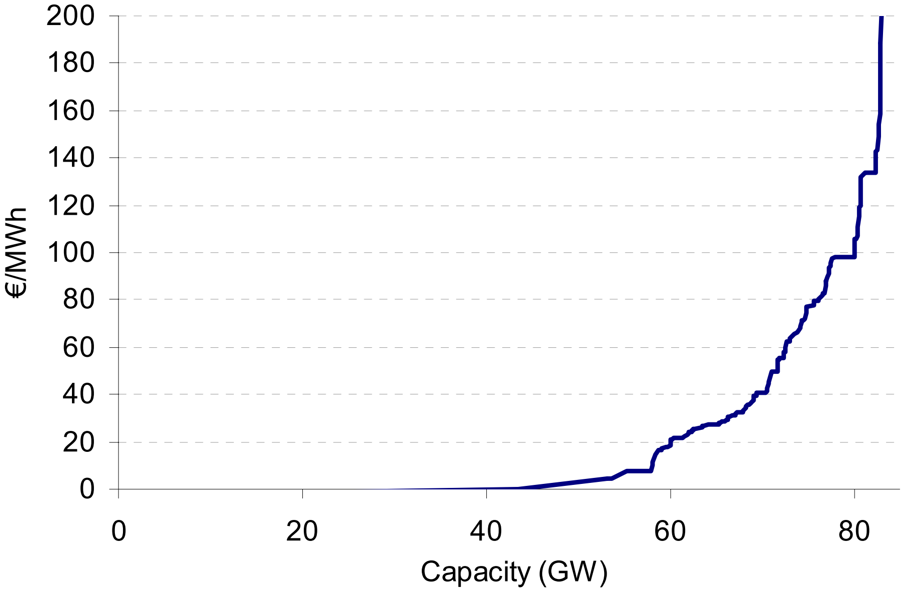


Figure 12. Marginal cost curve for the units in the model, excluding wind and run-of-river hydro power units. Reservoir hydro power, a block of 43 GW, has been assigned a zero marginal cost in the figure. For CHP units the value of heat has been assumed to be 10 €/MWh and it has been assumed that they can produce at highest efficiency.

The analysed year, 2005, was a rather typical year for hydro power inflow and reservoir levels. However, in mid Norway and in northern parts of the countries there were somewhat less water in the reservoir in the first part of the year and slightly more during the latter part of the year.

2.5 Grid constraints

Power transfer between areas is often limited by a given, direction specific maximum value for the transmission capacity. In reality the transmission capacity depends on the power system state and varies from one moment to another.

Transfer limits on certain important cuts define the power system states that are within "normal operating range". Factors that set the normal operating range are thermal loading limits of grid components, dynamic stability and voltage stability of the system. When operating in normal operating range, the power system can withstand any single contingency (N-1 criteria). The relationship between North-South transmission and AC import/export from/to Sweden is illustrated in Figure 13. In moments of export to Sweden attention has to be paid to damping of power oscillations. When importing over the AC interconnection in the North, further transmission to the South is limited by voltage stability criterion.

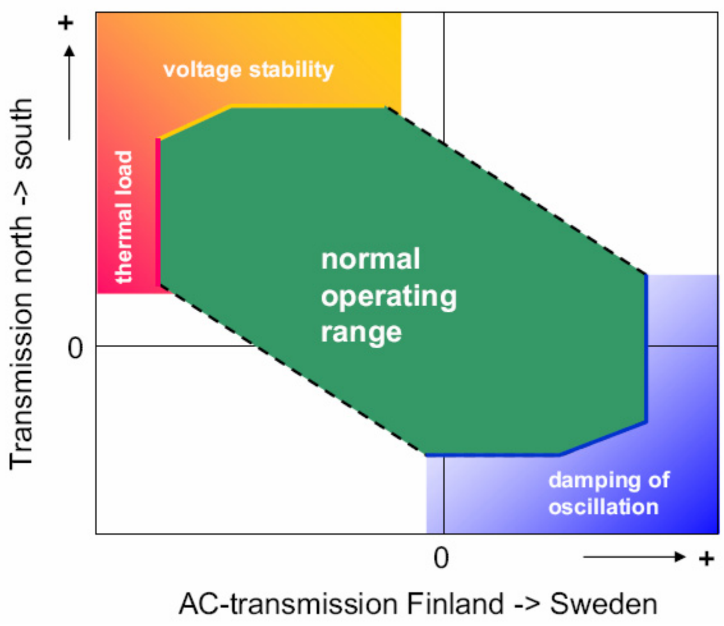


Figure 13. Factors limiting transmission in the Finnish grid [3].

It is clear that exact transmission capacities cannot be determined without detailed power system simulations. Nevertheless transmission constraints should be taken into account when simulating and analysing power flow between areas.

In the Wilmar model it is possible to set maximum capacities for the power flow between areas. In this study we are interested in the transfer in the North-South direction. The most important cut in the Finnish power system is called P1 and is located South of Oulu. In Figure 2 on page 10 this cut is labelled “B”. Other internal cuts that have transfer limitations in the simulations are cut A and C, see Table 5.

Table 5. Base case transfer limits that are used in the simulations.

	Cut A1	**Cut A2**	**Cut B**	**Cut C**
Northward	3000 MW	2500 MW	1600 MW	200 MW
Southward	4000 MW	3200 MW	2000 MW	200 MW

The transfer between Sweden and Finland is in the simulations limited to 1300 MW on the AC connection in the North and to 1350 MW on the DC connection in the South. The hourly import and export is determined by the Wilmar model according to marginal prices of generation in the countries of the market area. The import from Russia is set to constant 1050 MW which yields 9.2 TWh a year. Due to a lack of better information, it is assumed that the interconnector to Estonia is used to import constantly 250 MW even though it is likely that the cable is sometimes used for export.

A useful measure for the severity of congestion is the change that an increased transmission capacity of 1 MW brings to the price difference of two areas. This marginal price difference indicates how severe the congestion is and gives an indication of the benefit of increasing transmission capacity. The marginal price is the shadow value of the equation restricting the transmission capacity. It can be used as a measure likewise for internal cuts where congestion is handled by the TSO by counter-trade, as for connections between actual price areas.

Marginal price gives, however, only indicative information, since in practice grid reinforcements are lumpy and one has to evaluate the benefit of a step increase in transmission capacity. The benefit of the first MW capacity increase is greater than the benefit of following MW. Therefore it is useful to run the simulations also with increased transmission capacities in certain cuts. The simulations are therefore also run with increased transmission capacities of cuts A and B. The transmission capacity is increased with 500 MW at one cut at a time.

In order to evaluate the overall feasibility of grid reinforcement, the benefit of increased transmission capacity should be compared to the costs for reinforcement (construction and operation) and avoided costs (counter-trade). However, this is not done for the example presented in this report.

3. Results

When finally all generation and consumption data is gathered, it is time for the analyses phase. In this study, the impact of wind power on the regional power balance, power flow between the areas and congestion is calculated and visualised by using a purpose-made Matlab-application. Three different cases are simulated, namely 0 MW, 2000 MW and 4000 MW installed wind power.

3.1 Regional power balance

The dispatch conducted by the Wilmar model includes information on the location of the power plants that are chosen to produce power in each hour. In Figure 14 the yearly power production in each of the areas is shown for the three cases. Values in blue represent wind power production and values in red total generation by other types of power plants in that area.

According to the simulations wind power hardly impacts the total yearly production amounts of other power plants in area 1, 4 and 7. Wind power affects mostly generation in the areas 3 and 5 where this other production decreases by 4% and 6%, respectively, if 4000 MW wind power is installed in Finland. The generation with other than wind decreases in this case altogether with 4% in Finland. 2000 MW wind power reduces the regional production with roughly half compared to the reduction 4000 MW wind power causes.

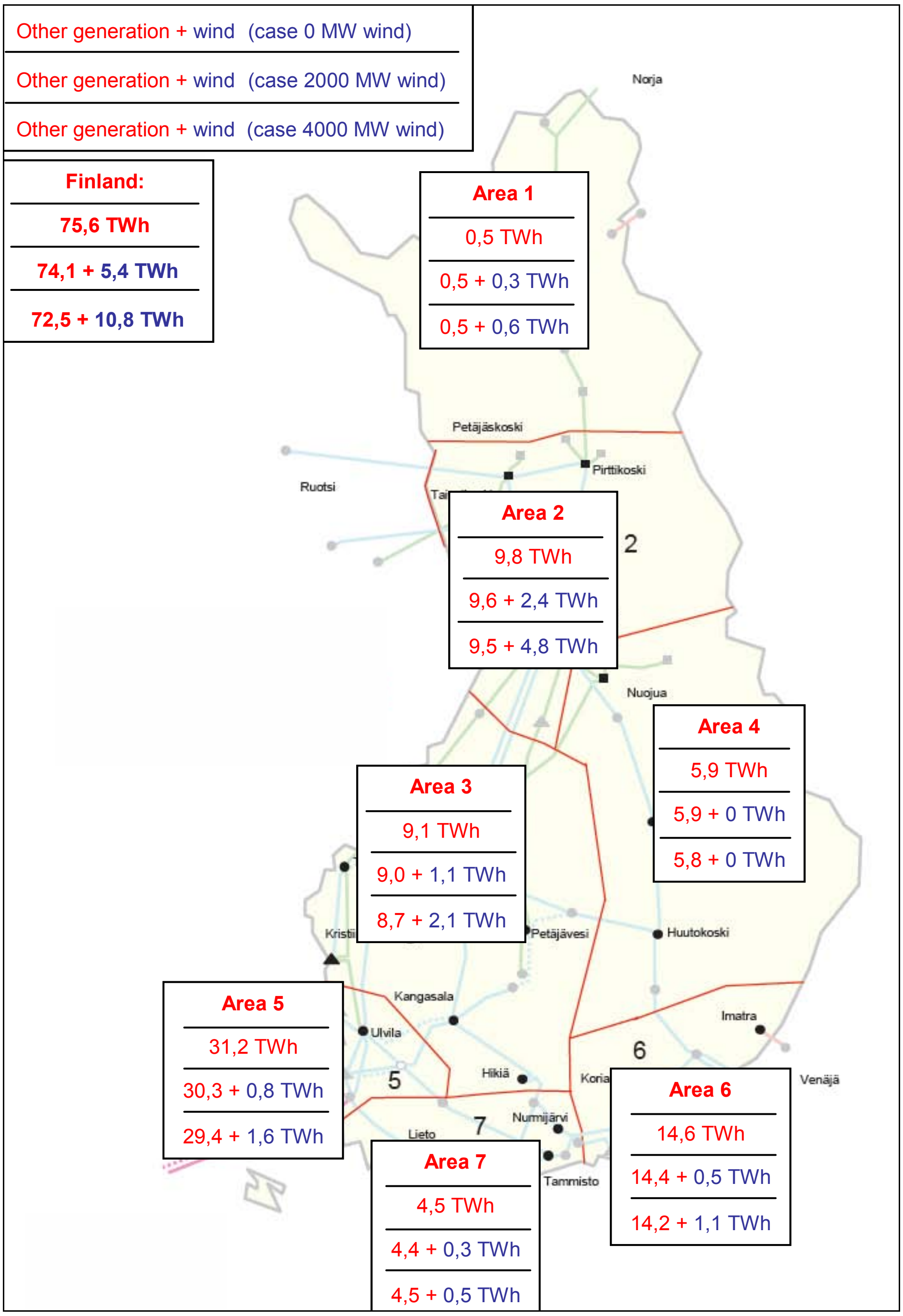


Figure 14. Regional other generation (in red) and wind power production (in blue) in the 0 MW, 2000 MW and 4000 MW wind power cases.

Table 6. Annual load, other production, wind power and net power for each area in TWh.

Case	[TWh]	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7
0 MW	Load	0,7	10,8	26,5	13,2	8,6	18,1	22,2
	Other production	0,5	9,8	9,1	5,9	31,2	14,6	4,5
	Net	**-0,3**	**-1,0**	**-17,4**	**-7,3**	**22,5**	**-3,6**	**-17,7**
2000 MW	Other production	0,5	9,6	9,0	5,9	30,3	14,4	4,4
	Wind power	0,3	2,4	1,1	0,0	0,8	0,3	0,5
	Net	**0,0**	**1,2**	**-16,5**	**-7,3**	**22,5**	**-3,5**	**-17,2**
4000 MW	Other production	0,5	9,5	8,7	5,8	29,4	14,2	4,5
	Wind power	0,6	4,8	2,1	0,0	1,6	0,5	1,1
	Net	**0,3**	**3,5**	**-15,7**	**-7,4**	**22,3**	**-3,5**	**-16,7**

With increased wind power, the areas 1 and 2 become overproduction areas from being underproduction areas, see Table 6. In the 4000 MW case the yearly wind power production equals 79% and 44% of the load in area 1 and 2, respectively. In area 5 wind power replaces on a yearly basis more or less the decrease in other production. In area 3 the wind power production exceeds the decrease of other generation and the net effect in this area is a reduced underproduction.

3.2 Replaced generation

Figures 15 and 16 illustrate what generation Finnish wind power replaces on a yearly basis according to the simulations.

2000 MW Finnish wind power reduces nuclear power in Finland with 0.5 TWh and 4000 MW wind power reduces nuclear power with 1.4 TWh. Corresponding values for coal are 0.5 TWh and 0.8 TWh, and for peat 0.2 TWh and 0.5 TWh.

On a Nordic level Finnish wind power replaces mostly coal. 2000 MW wind power replaces 3 TWh electricity produced by coal and 4000 MW wind power 4.5 TWh. Most of the coal reduction, i.e. around 80%, takes place in Denmark and only 15% in Finland. Nordic nuclear power production is reduced with 0.6 TWh and 1.7 TWh and Danish fuel oil with 0.4 TWh and 0.8 TWh. Most of the nuclear power reduction takes place in Finland.

Hydro power production is optimised and dispatched through the water-value. Wind power replaces therefore temporarily, but not on a yearly basis, hydro power. Somewhat different amounts of electricity are, however, produced by hydro power in the different wind power cases. As a result the reservoir levels at the end of the simulated year differ a bit and consequently the results from the cases are not absolutely comparable.

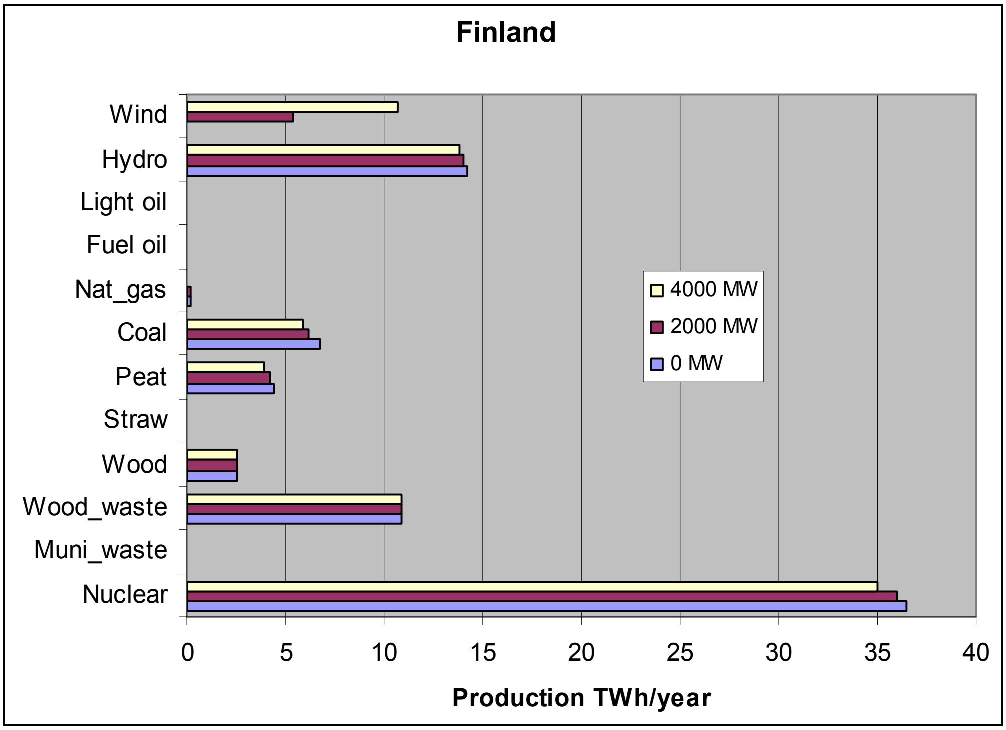


Figure 15. Yearly electricity production by fuel type in Finland for the Finnish wind power scenarios of 0 MW, 2000 MW and 4000 MW.

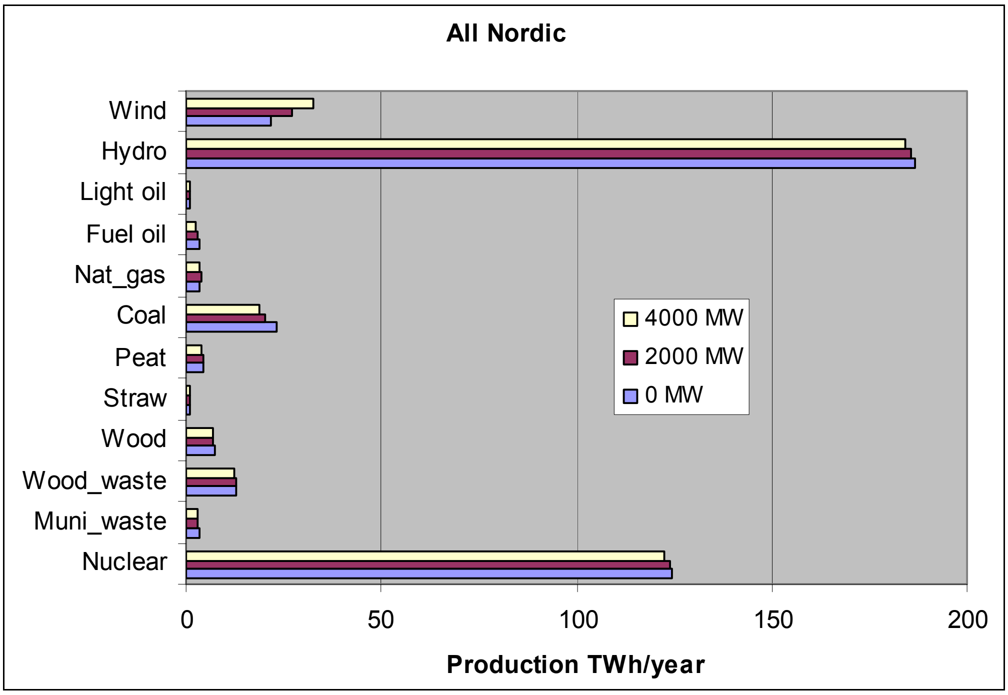


Figure 16. Yearly electricity production by fuel type in the Nordic countries for the Finnish wind power scenarios of 0 MW, 2000 MW and 4000 MW.

In windy periods wind power replaces according to the simulation results hydro power and import to a large extent, wood waste and coal a little, but occasionally also nuclear power. Figures 17 and 18 show an example of wind power replacing domestic hydro power and import a windy day. In that day the generation reduction actually takes place in Denmark at coal, fuel oil and natural gas plants. Finnish import turns into export in the afternoon.

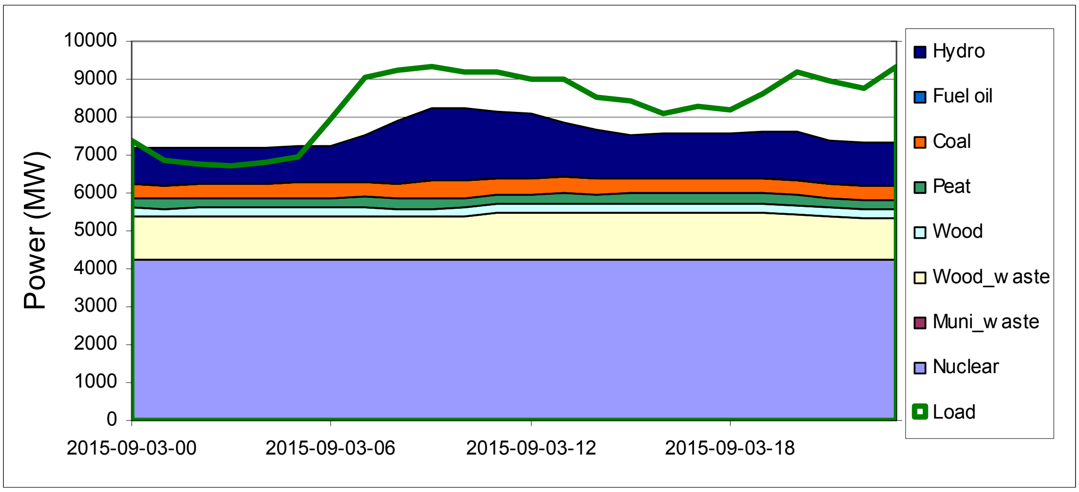


Figure 17. Finnish load and generation by fuel type during one day in the 0 MW wind case.

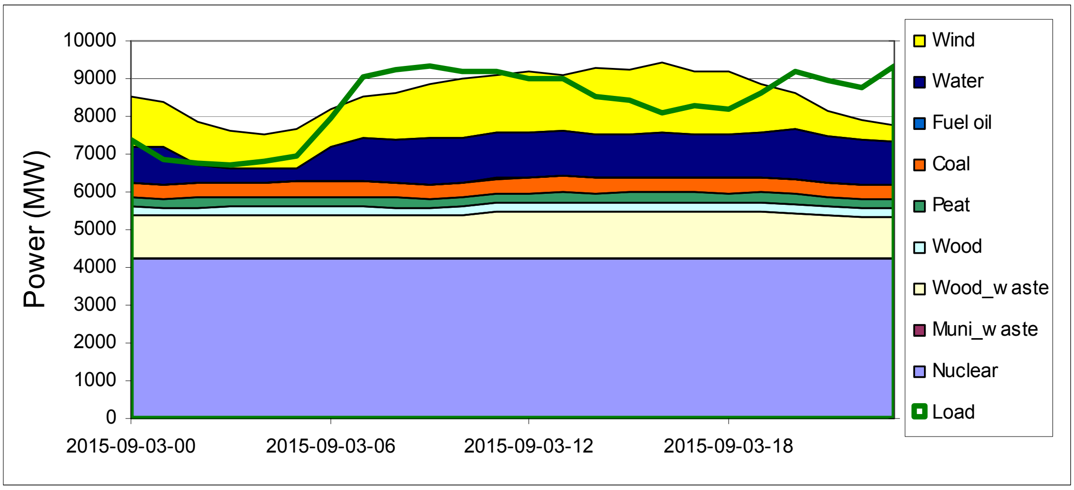


Figure 18. Finnish load and generation by fuel type during one day in the 4000 MW wind case.

It is interesting to note that according to the simulation results wind power replaces nuclear power mainly in June and in October. In June the electricity demand is low and only few power plants are in operation. In the simulation setup power import from outside the market area as well as wind power itself is fixed, so also nuclear power has sometimes to reduce its production.

In October the demand is higher than in June and more power plants are in operation. The electricity production of most of the CHP plants is modelled to directly depend on the heat demand. Furthermore, in October 2005 hydro power reservoirs are on a rather high level and there is less downward flexibility in hydro power. So again nuclear power flexes and reduces its production on the windiest days.

Whether nuclear power plants would vary their production from day to day in the future is doubtful, although it is technically possible. The simulation results just indicate what the dispatch would look like from an economic point of view in a system with those restrictions and limitations that are described in Chapter 2. In reality an increased flexibility in consumption or in the operation of CHP plants could possibly be the most efficient and feasible solution. District heat could be produced with electric resistance heaters instead of CHP plants when electricity gets really inexpensive. In rare situations of serious overcapacity, it could be easier to dump electricity generation from wind power itself rather than vary the output of nuclear power plants.

3.3 Import and export

Wind power has an impact on the power import and export. As the marginal cost of wind power is more or less zero, wind power replaces both domestic production and import.

In the simulations 2000 MW wind power that produces 5.4 TWh/year replaces on a yearly basis 3.9 TWh import. 4000 MW wind power producing 10.8 TWh/year replaces 7.6 TWh import. The majority of the import, as well as the reduction in import, come from Sweden. Direct import from Norway is small in all cases due to low cross-border capacity between Finland and Norway preventing any significant power exchange.

The import from the neighboring countries in each simulation case is presented in Table 7. The import from Estonia and Russia is fixed in the simulations. Import from Norway and Sweden is a result of the dispatch result of the market simulations with the Wilmar model.

Table 7. Import to Finland expressed in TWh/year for the different cases.

Import from	**0 MW wind power**	**2000 MW wind power**	**4000 MW wind power**
Sweden	13.0 TWh	9.3 TWh	5.7 TWh
Norway	0.4 TWh	0.3 TWh	0.1 TWh
Estonia	2.2 TWh	2.2 TWh	2.2 TWh
Russia	9.2 TWh	9.2 TWh	9.2 TWh

From the power system operation point of view a challenging situation is the combination of high wind power production and high import. The fear is that the wind power suddenly drops and all cross-border connections are fully in use and hence preventing a quick increase in import. In these situations there has to be enough fast responding reserves within the country. The simulation results are analysed in more detail in the following in order to see how likely a situation like this is.

In the 4000 MW wind power case the hourly wind power production exceeds 2000 MW in 1787 hours out of the 8748 hours in the simulated year, i.e. 20% of the time (Figure 20). Of these hours only 78 take place when the import from Sweden is at its maximum. All in all import is at its maximum during 623 hours a year in this scenario. In other words wind power production exceeds 2000 MW in 20% of the time, but only 13% of the hours with maximum import. The wind power production has to be high in order to have the possibility to decrease significantly in a short time. In the simulated 4000 MW case there is a situation of wind power production above 2000 MW and simultaneously maximum import in less than 1% of the hours.

The peak wind power production is 3690 MW (92% of installed capacity). The largest wind power production during maximum import is, however, only 3221 MW (81% of installed capacity) as can be seen in Figure 19.

The impact of wind power on power import is more apparent the more domestic wind power there is. The interconnectors are congested from Sweden to Finland during 883 hours in the 2000 MW case but only 623 hours in the 4000 MW case. In the 2000 MW case wind power production exceeds 1000 MW simultaneous as maximum import during 117 hours of the year, i.e. more often than in the 4000 MW case. Likewise the highest wind power production during maximum import is relatively seen somewhat higher in the 2000 MW case: 1703 MW or 85% of installed capacity compared to 81% in the 4000 MW case.

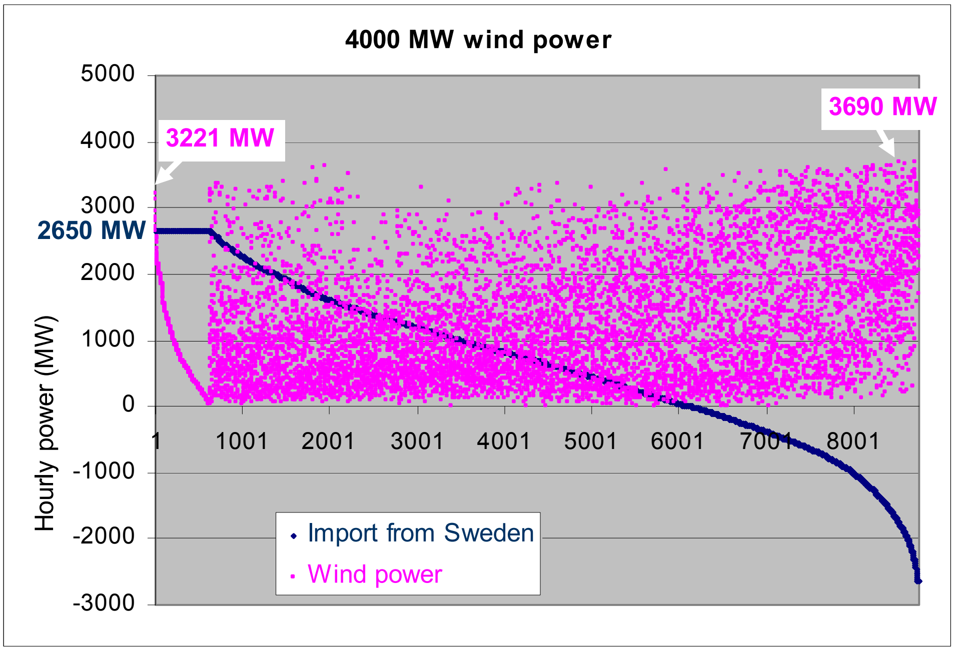


Figure 19. Hourly values for Finnish wind power production and import from Sweden in the 4000 MW wind power case sorted by the import.

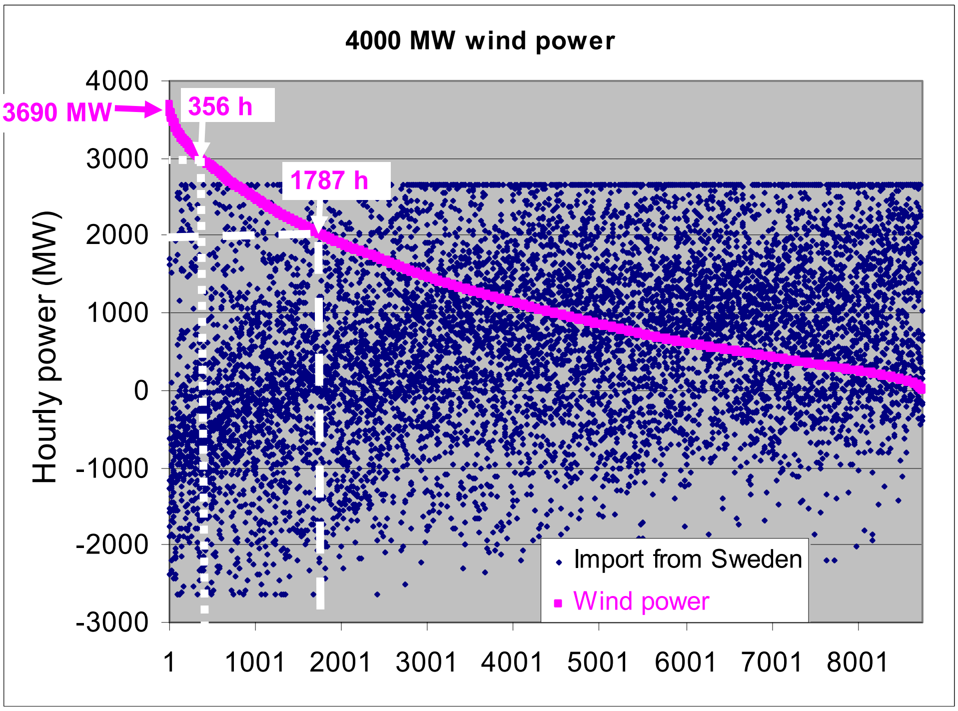


Figure 20. Hourly values for Finnish wind power production and import from Sweden in the 4000 MW wind power case sorted by wind power production.

3.4 Power transfer between the areas

3.4.1 Basic results

Wind power changes the power flow in two ways: directly by increasing the generation in areas with wind power, and indirectly by replacing generation that has higher marginal costs. The replaced generation can be located in the same or another area, or even abroad.

This Chapter analyses the amount and direction of electricity transfer between areas for different amounts of wind power. The number of hours with congestion on critical cuts is looked upon as well.

In the simulated cases transfer restrictions are implemented in the Wilmar model on three internal cuts, namely A1, B and C (shown in Figure 2), and naturally on cross-border transfer. The transmission capacities of Table 5 are used in the simulations.

Figures 21, 22 and 23 show the duration curves of the transmission over cut A1, cut B and cut C respectively in the 0 MW, 2000 MW and 4000 MW wind power cases. According to the simulation results the power flow in cut A1 goes always in the direction northwards. The reason is that in addition to the generation in South of Finland there is a substantial import South of cut A1: from Russia, Estonia and Sweden through the DC-cable. In the simulated cases 70% of the wind power is located North of cut A1 and thus wind power reduces clearly the power flow in cut A1.

The power flow in cut B is from North to South both with and without wind power most of the year. The transmission southward is limited to 2000 MW which results in 360 hours of congestion in the case with 0 MW wind power. 2000 MW wind power increases the congested hours to 670, and 4000 MW to 1050 hours.

In the 0 MW wind power case cut C is never congested. The transmission capacity is however low, only 200 MW. In the cases with wind power there is a need for more transmission capacity southward. In the 2000 MW wind power case cut C is congested 620 hours and in the 4000 MW case 1100 hours.

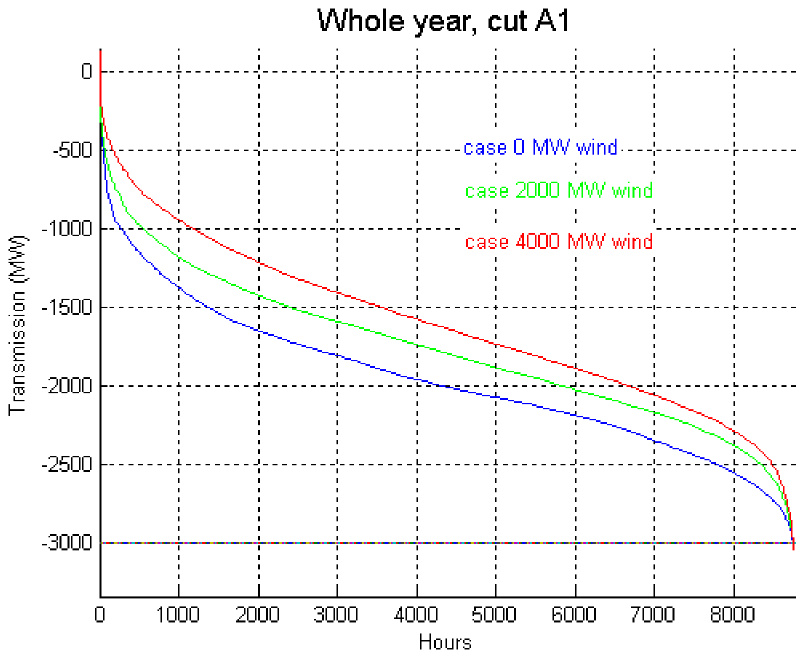


Figure 21. Duration curve of the transmission in cut A1. Positive values represent transmission from North to South.

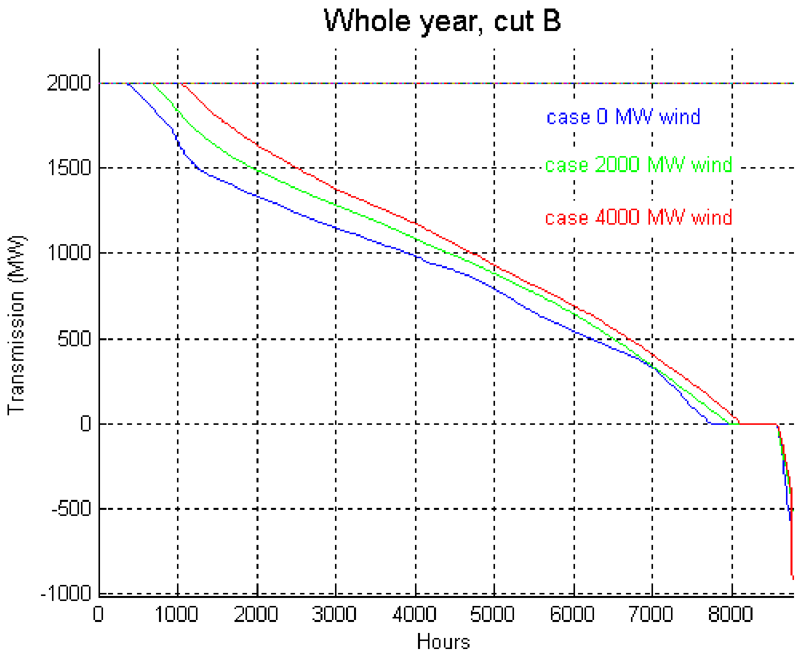


Figure 22. Duration curve of the transmission in cut B when the transmission capacity is 2000 MW. Positive values represent transmission from North to South.

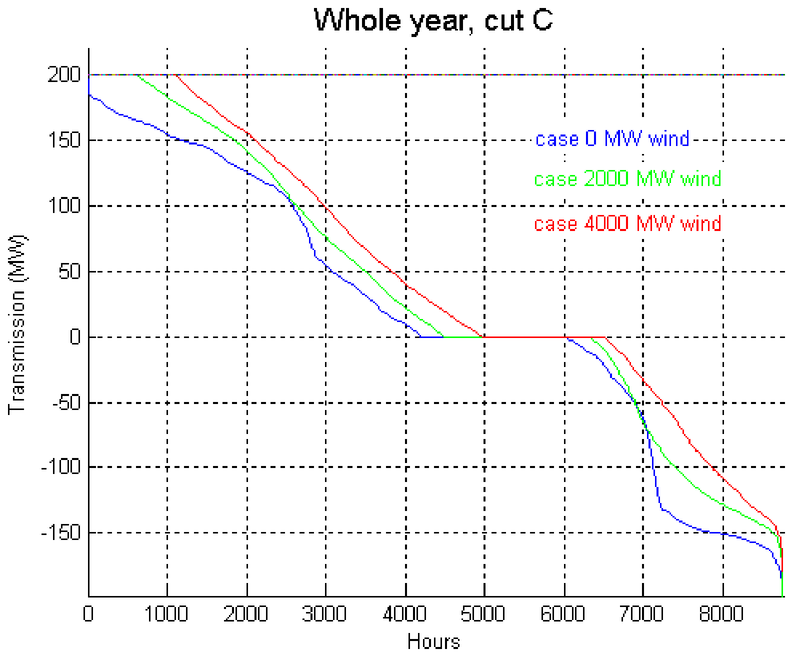


Figure 23. Duration curve of the transmission in cut C when the transmission capacity is 200 MW. Positive values represent transmission from North to South.

3.4.2 Dependance of time

The power flow impact of wind power depends on the whole power system situation and may therefore depend on the time of day and season. A good example of this is cut B in the example case: the cut is congested 400 hours in night time in the 4000 MW wind power case while it is never congested night time in the 0 MW wind power case, see Figure 24. Likewise there is no congestion in the 0 MW wind power case during summer and early autumn whilst 2000 MW and 4000 MW wind power causes congestion in cut B also during this time.

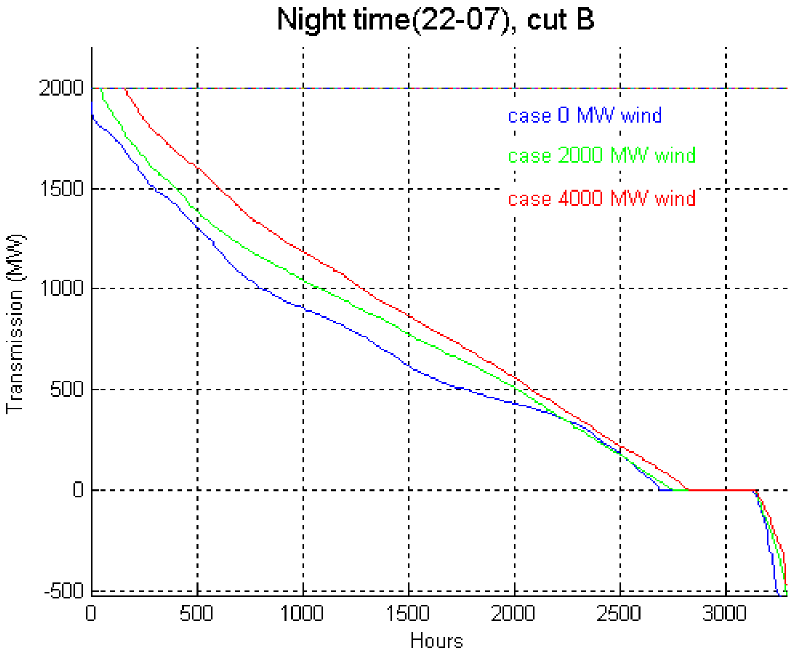


Figure 24. Duration curve of the night time transmission in cut B. Positive values represent transmission from North to South.

3.4.3 Severity of congestion

During hours when a transmission line is congested, the model gives a shadow prise, aka marginal price, for the connection. This indicates the benefit of one additional MW of transmission capacity between the areas. Marginal price gives, however, only indicative information, since in practice grid reinforcements are lumpy and one has to evaluate the benefit of a step increase in transmission capacity. One method is to run the simulations with increased transmission capacity on critical cuts.

In the example cases the transmission capacity southward in cut B is increased with 500 MW in order to see whether a transmission capacity of 2500 MW is enough to avoid congestion. The duration curves of the transmission on cut B given by the new simulation are shown in Figure 25.

According to the simulations, 4000 MW of wind power would triple the hours with a transmission need higher than 2000 MW southward in cut B compared to the same system without wind power (Table 8). An increase of the transmission capacity to 2500 MW would reduce the congested hours significantly in all cases.

The value of this additional transmission capacity was estimated based on the marginal prices of the congestion. The model indicates that there are much more important constraints in the Nordic system than those inside Finland. One of them is between north Finland and north Norway. As wind power penetration increases the value of the 500 MW line over cut B increases. In the base case the value is 0.32 M€/a, in 2000 MW case the value is 0.54 M€/a, and in the 4000 MW case the value increases to 0.82 M€/a. The value is calculated from the average marginal value between the cases with and without the new transmission line. The value of the new line starts to be comparable with the cost of the line in the wind cases especially since the power prices are lower in the model than what has been seen in the actual spot market as described in the next chapter.

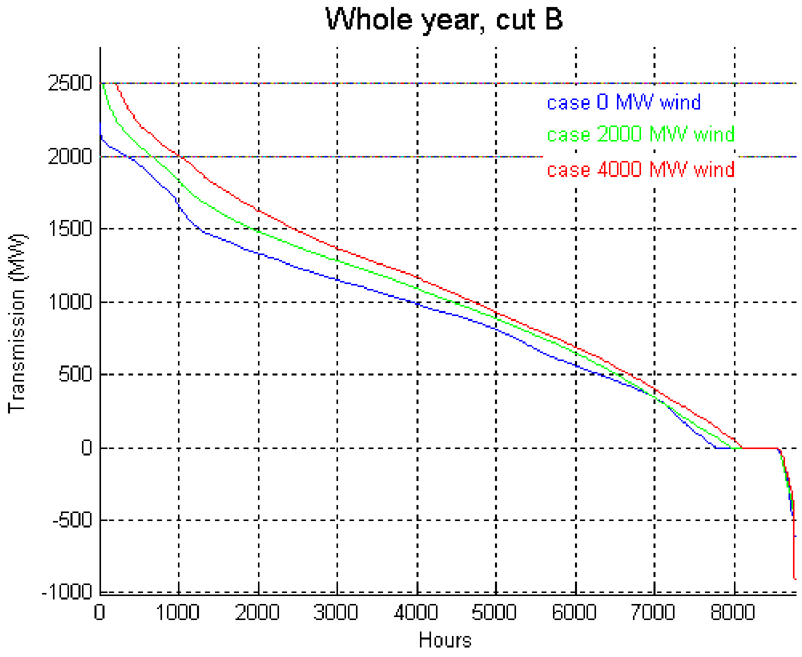


Figure 25. Duration curve of the transmission in cut B when the transmission capacity is increased by 500 MW to 2500 MW. Positive values represent transmission from North to South.

According to the simulations, 4000 MW of wind power would triple the hours with a transmission need higher than 2000 MW southward in cut B compared to the same system without wind power (Table 8). An increase of the transmission capacity to 2500 MW would reduce the congested hours significantly in all cases.

The value of this additional transmission capacity was estimated based on the marginal marginal prices of the congestion. The model indicates that there are much more important constraints in the Nordic system than those inside Finland. One of them is between north Finland and north Norway. As wind power penetration increases the value of the 500 MW line over cut B increases. In the base case the value is 0.32 M€/a, in 2000 MW case the value is 0.54 M€/a, and in the 4000 MW case the value increases to 0.82 M€/a. The value is calculated from the average marginal value between the cases with and without the new transmission line. The value of the new line starts to be

comparable with the cost of the line in the wind cases especially since the power prices are lower in the model than what has been seen in the actual spot market as described in the next chapter.

A new transmission line over Cut C was also analysed, but the connection is only rarely over the capacity even in the 4000 MW case and there is no need to upgrade the line according to the model results.

Table 8. Power flow direction and congested hours in cut B expressed as percentage of hours in the year.

	Direction		**Transmission need**	
Case	**South**	**North**	**>2000 MW**	**>2500 MW**
0 MW wind power	88 %	2 %	4 %	0 %
2000 MW wind power	91 %	2 %	8 %	1 %
4000 MW wind power	93 %	2 %	12 %	2 %

3.5 Electricity price

Electricity prices in the model runs were very low. The main reason is that there was too much production capacity compared to consumption. This drops the water value of hydro power very low as most of the time it replaces low marginal cost power production. Still, the relative differences between scenarios give an indication of the effect of wind power and additional transmission lines on the spot market prices (Figure 26). Average prices in Finland were lower than in the Nordic system on average as can be seen from the Figure 27. 2000 MW increase of wind power in Finland decreased spot prices in Finland by about 1.5 €/MWh and Nordic average prices by about 1.4 €/MWh.

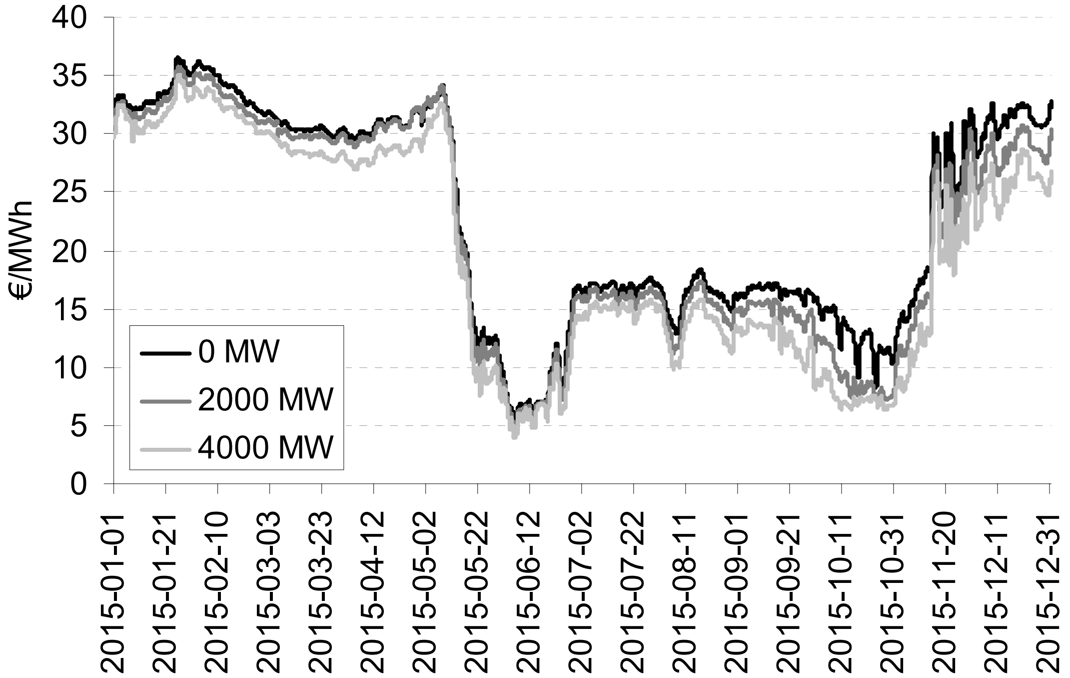


Figure 26. 24 hour running average of spot market prices in the different scenarios for Finland.

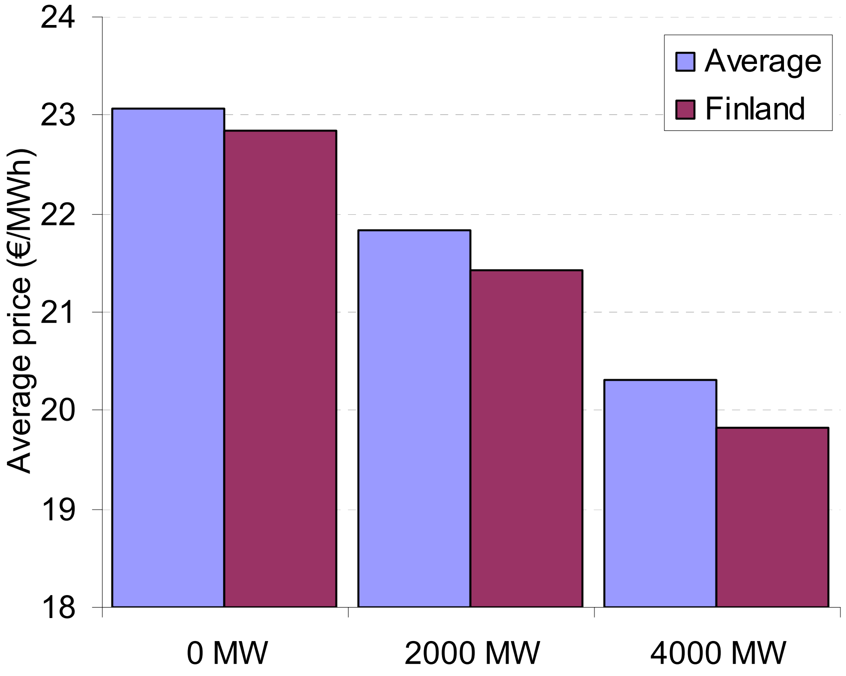


Figure 27. Average power prices in the Nordic system and in Finland during the modelled year in the different scenarios.

Inside Finland there would be a small price difference between cut B and a very small price difference over cut B. Those were the only price differences seen in the scenarios. The average spot price difference over cut B was 0.15 €/MWh in the base scenario and 0.2–0.30 €/MWh in the wind scenarios. Additional transmission line over cut B would erase the price difference in base scenario and decrease it strongly in wind scenarios. Part of the price difference would move to the cut between FI_1 and FI_2.

3.6 Power system operating point

The operating point of the Finnish power system can be defined by

- the import along AC connections from Sweden and
- the North-South power transfer over cut B

as described in Chapter 2.5.

The operating point for each hour in the 4000 MW wind power case is plotted in Figure 28. It can be seen that the area covered with operating points is of similar shape as the normal operating range in Figure 13.

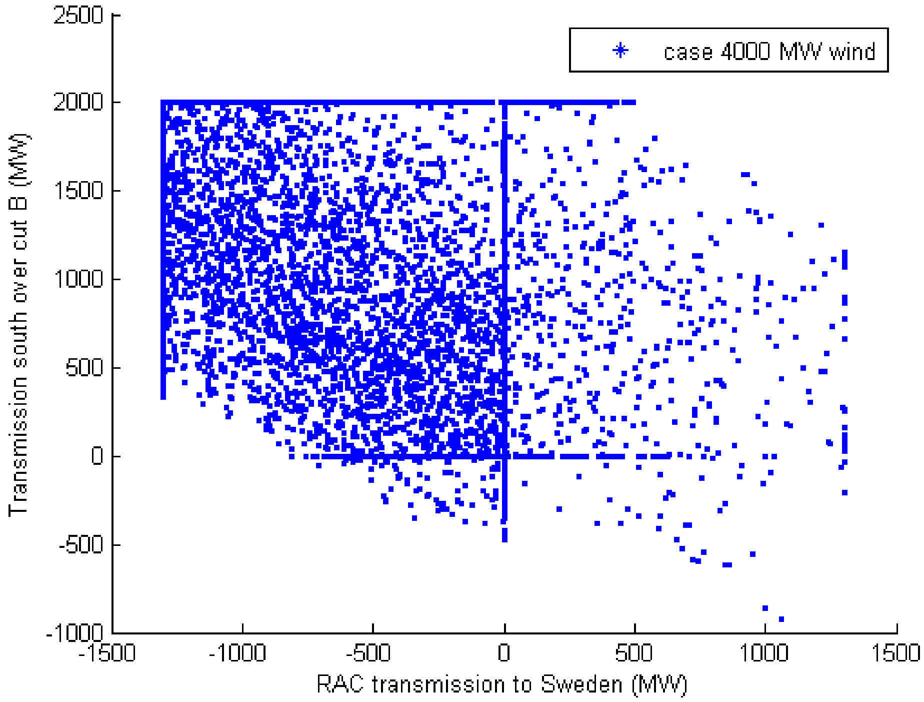


Figure 28. Operating points in the 4000 MW wind power case.

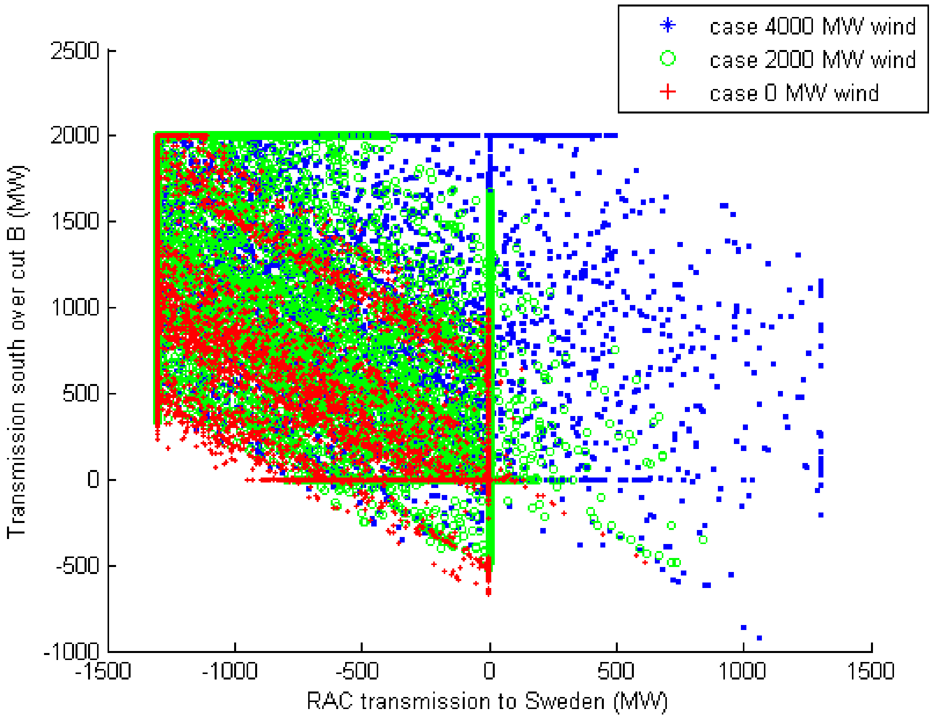


Figure 29. Operating points in the 0 MW, 2000 MW and 4000 MW wind power cases.

Figure 29 illustrates the impact of wind power on the operating point. In this figure the operating points in the 0 MW and 2000 MW wind power cases are plotted on top of the 4000 MW wind power case. According to the simulations it can be concluded that the more wind power there is

- the more often is cut B congested
- the *more power (in MW)* is exported to Sweden over the AC-connection
- the more *often* is Finland exporting power to Sweden.

The large number of operating points laying exactly on the x- and y-axis is due to the feature of the market model. In cases of equal marginal production costs in two areas, the model chooses the production plants so that a minimum of power is transferred between two areas.

In these simulations constant values for the maximum transmission limit between areas and countries were used. In reality the limit would change according to the power system state and the operating point plot from one full year would not have so sharp edges as in Figure 28 and Figure 29.

4. Conclusions

This report describes a method on how to analyse wind power influence on power transfer between different areas in a power system. It can be concluded that the task is challenging since 1) there are no readily available tools, 2) much data is needed and 3) many assumptions have to be made.

In order to study the power transmission between the areas in a meshed system the influence of a given generation or load change on a given line flow should be studied by power flow calculation. If one does not have, or does not wish to use, a grid model with impedances or power transfer distribution factors for the modelled system, the system has to be reduced to a non-meshed or radial form. When no parallel and diagonal alternative routes for the power flow exist in the model, the flows can be solved simply by addition and subtraction of domestic generation and consumption and cross-border-flows. This method only estimates the severity of congestions over the cuts under study and should therefore not be used for designing the characteristics of new transmission lines.

There is a need for a model tool that combines power flow and dispatch models in a setting where there is large scale wind power, reservoir hydro power with complicated usage restrictions, and combined heat and power production. Since this was not available, a dispatch model without parallel transmission lines inside Finland was used. The use of separate power flow model to check the results would have increased the robustness of the results, but this was outside the scope of the study.

It is of utmost importance that the wind or wind power data, whichever is used, is representative and suitable for creating wind power series for large areas. Spatial correlation and smoothing effect has to be present on a correct level.

The future load pattern is reasonably predictable. If historical hourly data is available, a reasonably good estimate can be made easily by up-scaling. The availability of hourly consumption data for smaller areas might be an obstacle. Scenarios on total consumption can on the contrary usually be found from various sources. Hourly time series can be created using consumption indexes, but this requires a large effort as shown in the example case in this report.

The uncertainty increases when predicting years far in the future. It is mainly due to assumptions on new generation investments (size, location, type/fuel) and on marginal price of fuels and CO_2 emission. In a proper study, the results should include sensitivity analysis on the most important factors.

With proper input data and simulation tools it is possible to analyse the impact of wind power on numerous matters. Interesting analysis can be done for example on the regional power balance, amount and direction of power transfer between the areas as well as congestion on critical cuts. One can get results showing location, type and amount of generation that wind power replaces, changes in import and export due to wind power, and many other interesting matters.

This report presents the simulation results of a fictitious example with 0 MW, 2000 MW and 4000 MW of wind power installed in a future Finland. With the data and assumptions made the simulations give following main results:

- Cut A is not congested.
- A new transmission line over cut B might be economic in the wind scenarios.
- Situations with simultaneously high wind power production and high import are rare as wind power replaces import to a large extent.
- The more wind power there is in Finland,
    - the more often is cut B congested
    - the *more power* is exported to Sweden over the AC-connection

the more *often* is Finland exporting power to Sweden.

References

1. Holttinen, H., Lemström, B., Meibom, P., Bindner, H., Orths, A., Hulle, F. van, Ensslin, C., Hofmann, L., Winter, W., Tuohy, A., O'Malley, M., Smith, P., Pierik, J., Tande, J.O., Estanqueiro, A., Ricardo, J., Gomez, E., Söder, L., Strbac, G., Shakoor, A., Smith, J.C., Parsons, B., Milligan, M. & Wan, Y.-H. Design and operation of power systems with large amounts of wind power.State-of-the-art report. Espoo: VTT, 2007. 119 p. + app. 25 p. VTT Working Papers 82. ISBN 978-951-38-6633-4. http://www.vtt.fi/inf/pdf/workingpapers/2007/W82.pdf. Visited 1.7.2008.

2. Seppälä, A. Load research and load estimation in electricity distribution. Espoo: VTT, 1996. VTT Publications 289. 118 p. + app. 19 p. http://www.vtt.fi/inf/pdf/publications/1996/P289.pdf. Visited 1.7.2008.

3. Koskinen, M. Kantaverkon suunnittelu. Lecture 7.2.2008, course S-18.3201, Helsinki University of Technology. http://powersystems.tkk.fi/opinnot/S-18.3201.htm. Visited 12.3.2008.

4. http://www.wilmar.risoe.dk.

VTT Working Papers

108 Hannele Antikainen, Asta Bäck & Pirjo Näkki. Sosiaalisen median hyödyntäminen paikallisissa mediapalveluissa. 2008. 64 s.

109 Raine Hautala, Pekka Leviäkangas, Jukka Räsänen, Risto Öörni, Sanna Sonninen, Pasi Vahanne, Martti Hekkanen, Mikael Ohlström, Bengt Tammelin, Seppo Saku & Ari Venäläinen. Benefits of meteorological services in South Eastern Europe. An assessment of potential benefits in Albania, Bosnia-Herzegovina, FYR Macedonia, Moldova and Montenegro. 2008. 63 p. + app. 35 p.

110 Jaana Leikas. Ikääntyvät, teknologia ja etiikka. Näkökulmia ihmisen ja teknologian vuorovaikutustutkimukseen ja -suunnitteluun. 2008. 155 s.

111 Tomi J. Lindroos. Sectoral Approaches in the Case of the Iron and Steel Industry. 2008. 58 p. + app. 11 p.

112 Johan Mangs. A new apparatus for flame spread experiments. 2009. 50 p. + app. 27 p.

113 Stephen Fox & Brent Stucker. digiproneurship. New types of physical products and sustainable employment from digital product entrepreneurship. 2009. 29 p. + app. 6 p.

114 Päivi Parviainen, Juha Takalo, Susanna Teppola & Maarit Tihinen. Model-Driven Development. Processes and practices. 2009. 102 p. + app. 4 p.

115 Kim Björkman, Juho Frits, Janne Valkonen, Keijo Heljanko & Ilkka Niemelä. Model-based analysis of a stepwise shutdown logic. MODSAFE 2008 Work Report. 2009. 35 p. + app. 4 p

116 Erika Holt, Hannele Kuosa, Markku Leivo & Erkki Vesikari. DuraInt-Project Workshop. Effect of interacted deterioration parameters on service life of concrete structures in cold environments. 2009 32 p

117 Paula Järvinen, Kai Puolamäki, Pekka Siltanen & Markus Ylikerälä. Visual analytics. Final report. 2009. 45 p. + app. 3 p.

118 Anna-Maija Hietajärvi, Erno Salmela, Ari Happonen & Ville Könönen. Kysyntä- ja toimitusketjun synkronointi metalli- ja konepajateollisuudessa Suomessa. Haastattelututkimus. 2009. 33 s. + liitt. 3 s.

119 Timo Korhonen & Simo Hostikka. Fire Dynamics Simulator with Evacuation: FDS+Evac. Technical Reference and User's Guide. 2009. 91 p.

120 Veikko Kekkonen & Göran Koreneff. Euroopan yhdentyvät sähkömarkkinat ja markkinahinnan muodostuminen Suomen näkökulmasta. 2009. 80 s.

121 Rinat Abdurafikov. Russian electricity market. Current state and perspectives. 2009. 77 p. + app. 10 p.

122 Bettina Lemström, Juha Kiviluoma, Hannele Holttinen & Lasse Peltonen. Impact of wind power on regional power balance and transfer. 2009. 43 p.

ISBN 978-951-38-7183-3 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN 1459-7683 (URL: http://www.vtt.fi/publications/index.jsp)