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WILMAR

Fluctuations and predictability of wind and hydropower

Deliverable D2.1

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June 2004

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Abstract (max. 2000 char.):

The report forms the deliverable D2.1 of the EU supported project Wind Power Integration in a Liberalised Electricity Market (WILMAR). The handling and generation of the necessary wind and hydro time series for the project's power system planning simulation model is described. The wind power and the hydro power time series on hourly basis are generated on basis of real data for all the geographical regions included in the analysis in order to realistically represent the various correlations in time and displacement. Models have been developed to generate various realistic future time series based on the past. One specific problem addressed is to simulate local wind power predictions hours ahead for each area.

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Contents

Preface 4

1 Introduction 5

1.1 The WILMAR project 5
1.2 WP 2: Analysis of fluctuations and predictability 7

2 Wind data 8

2.1 Wind data time series 8
2.2 Data set for Norway 12
2.3 Data set for Sweden 12
2.4 Data set for Finland 13
2.5 Data set for Denmark 14
2.6 Long term yearly production data 15

3 Large scale wind power production 16

3.2 Frequency distributions of wind power production 20
3.3 Seasonal variation of wind power production 22
3.4 Diurnal variation of wind power production 24
3.5 Persistence of wind power production 25
3.6 Correlation of wind power production 28
3.7 Short term variations of wind power production 30
3.8 Predictability of wind power production 36
3.9 Representative data for large scale wind power production 38

4 Wind models 41

4.2 Wind power model 44
4.3 Wind power prediction simulation model 45

5 Hydro data 52

5.1 Inflow data 52
5.2 Differences between regions 56
5.3 Controllable, uncontrollable inflow and flood 56

6 Correlation between wind/hydro/temperature 58

6.1 Temperature dependence of wind power production and load 58
6.2 Correlation of hydro inflow and wind power production 60
6.3 Example years 2000-2002 compared to long term average 61

7 Final remarks 61

8 References 62

Annex 64

Preface

The present report is part of the project Wind Power Integration in a Liberalised Electricity Market (WILMAR) supported by EU (Contract No: ENK5-CT-2002-00663). The report forms the contractual deliverable D 2.1 as defined in the Contract.

The present report presents and describes how the fluctuating wind and hydro data time series are handled and generated in the WILMAR project. More data will be provided, more analysis will be carried out after the issue of the present report and the models will be further developed within the project. The end-of-project status and results will be presented at that time in a supplementing report.

Most of the wind and hydro data have kindly been provided for the project for free by the project partners, Eltra and others. In order to have data for all WILMAR Regions additional commercial data may be purchased for the project.

Per Nørgaard, RISØ, has edited the report with contributions from Gregor Giebel, RISØ, Hannele Holttinen, VTT, Lennart Söder, KTH and Astrid Petterteig, SINTEF.

1 Introduction

The handling and generation of the necessary wind and hydro time series for the project's power system planning simulation model is described. The wind power and the hydro power time series on hourly basis are generated on basis of real data for all the geographical regions included in the analysis in order to realistically represent the various correlations in time and displacement. Models have been developed to generate various realistic future time series based on the past. One specific problem addressed is to simulate local wind power predictions hours ahead for each area.

Both wind power and hydro power are stochastic in nature, but on different time scales. The hydro inflow may vary from hour to hour, but the geographical spreading of the collection in combination with the dam storages result in a smoothing of the available hydro power. The fluctuations are therefore specified on weekly, seasonal or annual basis. The wind power however will fluctuate from one minute to the next. The aggregated wind power from more wind turbine units within an area will smoothen the fluctuations, but the fluctuations from one hour to the next may be significant.

For both the wind power and the hydro power the fluctuations may be correlated in both time and space. In order to be able to represent the various complex cross correlations the simulation of wind and hydro power data are based on real time series.

The raw wind data time series forms the basis for generation of wind power time series to be used as input to the WILMAR Planning Model. The Planning Model will need two types of wind power time series data: wind power estimated by region on hourly basis for one full year and wind power prediction scenarios simulated by region.

The raw wind data time series provided are quality checked, described and characterised. The quality will be tested by comparisons of neighbouring data sets. The data will be sufficiently described to be able to normalise and scale the data. The data will be analysed in order to identify relevant characteristics convenient for an easy comparison and evaluation of the various data series.

The raw wind data time series will be organised in a database together with parameters that enable the extraction of corresponding normalised time series that easily feed into the wind power generation models.

The raw wind data time series are provided either as wind speed data for a specific site or as (aggregated) wind power data for a specific area. Models have been developed to generate up-scaled, aggregated wind power time series on hourly basis for each of the WILMAR Regions.

In addition models have been developed to simulate sets of realistic wind power forecast scenarios for each WILMAR Region.

1.1 The WILMAR project

A fast introduction of large amounts of intermitting renewable power production as wind power can cause technical and economic problems of the power systems. These problems might arise due to unpredictability of wind power or due to unbalance between local power demand and intermitting power produced causing grid instabilities.

The main objective of the WILMAR project is to investigate these problems and to develop a modelling tool, which can be used to simulate alternative solutions providing a firm basis for decision making by system operators, power producers and energy authorities. Both the possibilities for integrating fluctuating power production by optimising the interaction of the existing units in a given electricity system, the possibilities lying in power exchange between regions, and the performance of dedicated integration technologies like electricity storage are evaluated.

The modelling and simulation efforts can be divided into two parts. One part consists in an investigation of the issue of system stability, i.e. the wind integration aspects connected to the fast (below 10 minutes) fluctuations in the wind power production, with the use of dedicated power system simulation tools. It includes the analysis of a number of case studies especially selected for large-scale integration of renewable energy generation and with expected potential stability problems.

Secondly the wind integration ability of large electricity systems with substantial amounts of power trade in power pools is investigated. With the starting point in existing models an hour-per-hour simulation model is developed, and this modelling tool is used to investigate the technical and cost issues of integrating large amounts of wind power into the electricity system. The model will cover the two power pools: NordPool and European Power Exchange, i.e. Germany, Denmark, Norway, Sweden and Finland. The developed model will be tested by different end-users, e.g. systems operators and power producers, which are expected to be users of the final model as well.

Finally the results obtained will be summarised and used to provide recommendations about the technical integration possibilities, the integration costs of wind power and the organisation of electricity markets and power pools.

The work in the WILMAR project is organised in the following work packages:

WP 1: Project management

WP 2: Analysis of fluctuations and predictability

WP 3: Description of the electricity system in 2010

WP 4: Emission trading and green markets

WP 5: System stability analysis

WP 6: Development of planning tool

WP 7: Distribution of the integration costs

WP 8: End-user testing of planning tool

WP 9: Recommendations

WP 10: Dissemination

The relations between the work packages are illustrated in Figure 1.

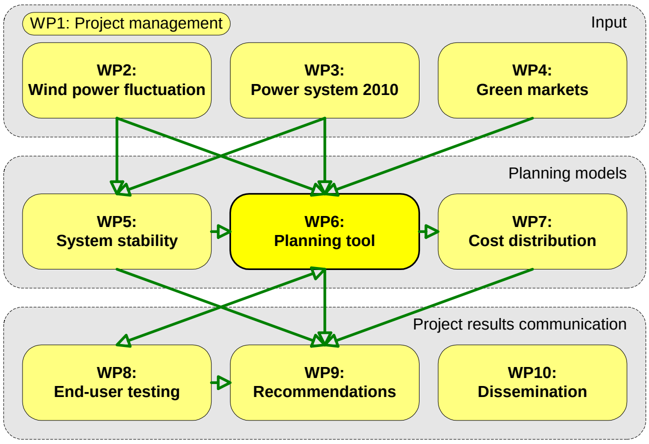


Figure 1: Illustration of the relation in terms of data flow between the work packages in the project.

The project partners are:

- Risø National Laboratory (RISOE)
- Elsam (ELSAM)
- SINTEF Energy Research (SINTEF)
- Kungliga Tekniska Högskolan (KTH)
- Technical University of Denmark (DTU)
- Elkraft System (ELKRAFT)
- University of Stuttgart, Institute for Energy Economics and the Rational Use of Energy (USTUTT/IER)
- Nord Pool Consulting (NPC)
- Technical Research Centre of Finland (VTT)

The modelling efforts in WP5 and WP6 will require substantial amounts of input data, which will be provided in WP2 and WP3.

Below the work package WP 2 is further described.

1.2 WP 2: Analysis of fluctuations and predictability

The purpose of WP2 is to analyse the size of the fluctuations in the power production from wind turbines and the precision of the wind power prediction tools existing today. As part of the analysis the reduction in the size of the fluctuations of wind power when the production from geographically separate wind turbine farms is added will be estimated. Also the variation from year to year of the wind power production will be investigated. Part of the output from this work package will be hour-per-hour time-series for the aggregated wind power production from each pricing region. Another output will be an algorithm simulating the performance of existing wind power prediction tools for use in WP6.

The variation in the hydropower production during the year and from year to year will also be modelled in WP2. An important issue when analysing the water flow to hydropower stations is, how much of the water flow can be stored in water reservoirs, and how much must be used immediately.

In the Contract the WP2 is defined by its objectives and work as follows:

Objectives:

- To provide time series for wind power production and hydro power production as a data input to WP5 and WP6. The time series must reflect the variation in wind power production and hydropower production from year to year. The time series for wind power production must reflect the short-term fluctuations in wind power and include the geographical smoothing occurring when the wind turbine sites in a given pricing region are added.
- To give an algorithm for the prediction of wind power from one to 36 hours ahead for use in WP6, which simulates the precision of the wind power prediction tools and methods developed today.

Description of work:

WP2.1 Analysis of fluctuations and predictability of wind power

- Collection of measured wind power production time series from the countries participating in the project.
- Characterisation of the time variation of the wind power production from a single site.

- Characterisation of the geographical smoothing of the fluctuations occurring when wind power production from geographical separated sites is added.
- Construction of time series for the wind power production in a given price area.
- Analysis of the predictability of the wind power production from one to 36 hours ahead. Developing an algorithm that simulates the predictability of wind power for use in WP6.

WP2.2 Analysis of the variation in the water flow to hydro power stations

- Analysis of the time variation during the year and from year to year of the water flow to hydro power stations in a given price area.
- Analysis of how much of the water flow can be stored and how much must be used immediately.

WP2.3 Analysis of correlations

- Analysis of the correlation between wind power production and water flow to hydro power stations.
- Analysis of the correlation between wind power production and space heating demand, i.e. the correlation between wind power production and combined heat and power production.

2 Wind data

The wind data for the simulation model is generated based on real wind data for the Regions within the study.

2.1 Wind data time series

The data used in the project is the measured output of wind turbines and wind speed measurements. The advantage of using realised wind power production data is to get the real wind farm output. When converting wind speed data to power production, there will always be some error, especially if the single point measurement is to represent a larger wind farm area. There will also be the effect of technical availability in the data, some of the turbines being serviced or faulty.

As wind power production data is limited in Finland, Norway and Sweden, also hourly wind speed measurement data was used to complement the production data. An effort has been made to make single measurement point data represent wind farm production.

The original time series provided for the project – here the wind speed and wind power time series – are called the raw data time series. These raw data time series together with their relevant characteristic parameters are organised in a database – the WILMAR Wind Database.

The raw data time series consist of real, historical data on hourly basis for full years – for 2000, 2001 and 2002. For each WILMAR defined Region the project collects as many time series as possible available for free. At least one raw wind time series is provided for each WILMAR Region.

Each raw data time series are pre-analysed in order to characterise the data. The extensive work for gathering data included a check up to make sure that the time shifts from winter and summertime were taken the same way in all time series collected, to keep all hourly values synchronous.

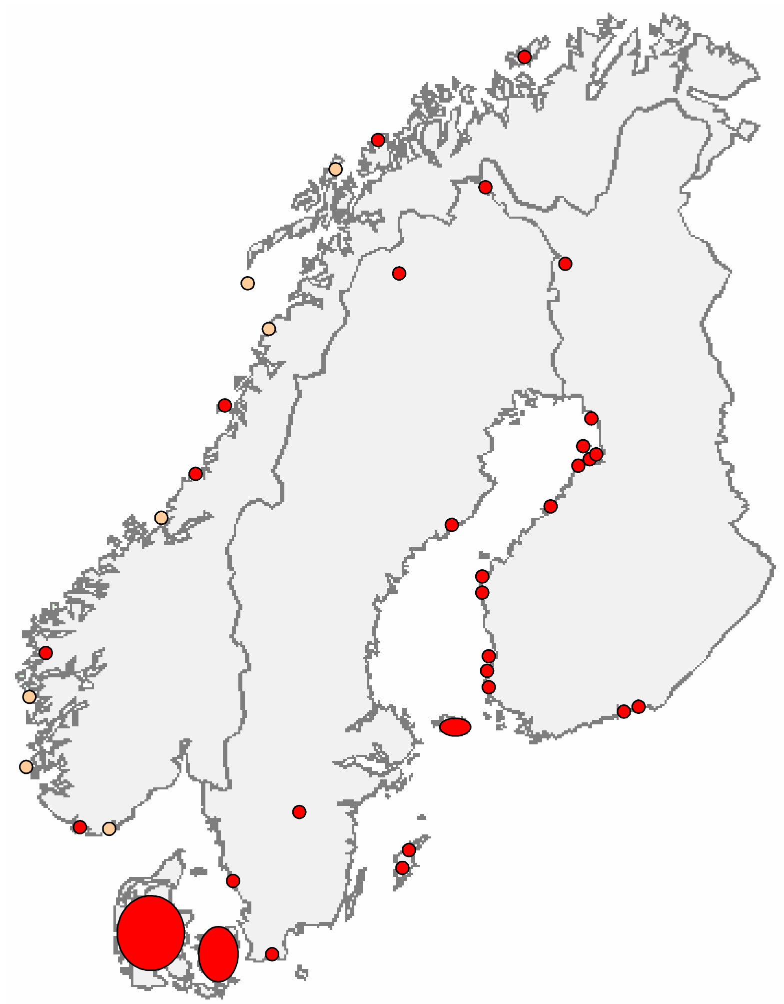


Figure 2. Data for hourly wind power production was available from 21 sites in Finland,6 sites in Sweden, 6-12 sites in Norway (the lighter coloured sites only for part of the time) and the aggregated total production of hundreds of sites in Denmark West and East.

Description of raw data

The description of each raw data time series include:

- The location of the site (for wind speed or single wind farm power data) or the area (for aggregated wind power data)
- The specific WILMAR region / area
- The height level of instrument and terrain characteristics for the site (for wind speed data) or the necessary specification of the wind turbines (for wind power data).

Pre-analysis of raw data

The pre-analyses of the raw data time series will include:

- Finding possible cut-out wind speed situations. This is relevant when using the power-to-wind model described in chapter 4.
- Calculation of average wind speed, ‘calm’ periods duration statistics,

- The relative annual energy production (relative to installed capacity).

WILMAR Wind Database

All the wind raw data time series together with their relevant characteristic data are organised in and available for the project simulations through a database – the WILMAR Wind Database. The wind data time series extracted from the database are normalised to be easily comparable and easy to upscale and combine. The wind speed data will be normalised to 100 m height level, a low and uniform surface roughness (0.01 m roughness length for the logarithmic vertical wind speed profile) and flat terrain. The wind power data are normalised to represent the aggregated power output relative to the installed power capacity.

Wind power production data analysis

The data used in the analysis of large scale wind power production is realised hourly wind power production time series from 4 Nordic countries (Figure 2). . German data has not been included in the analysis so far as access to the data is restricted. Data and analysis have in a high degree been provided to the project from a thesis work co-financed by WILMAR (Holttinen, 2003b)

Nordic data set was formed from the data sets of the 4 countries. The production at each hour was a simple average of the % of capacity production of the 4 countries. In terms of capacity this would mean setting for example 3000 MW in each country, a total of 12 000 MW. This is somewhat theoretical, as Denmark is now dominating the installed wind power, and probably will be for quite some time. The wind energy potential, however, is probably as large in all the 4 countries, when taking the offshore wind power potential in Sweden and Finland into account.

The time zone difference for Finland was taken into account when outlining the Nordic data.

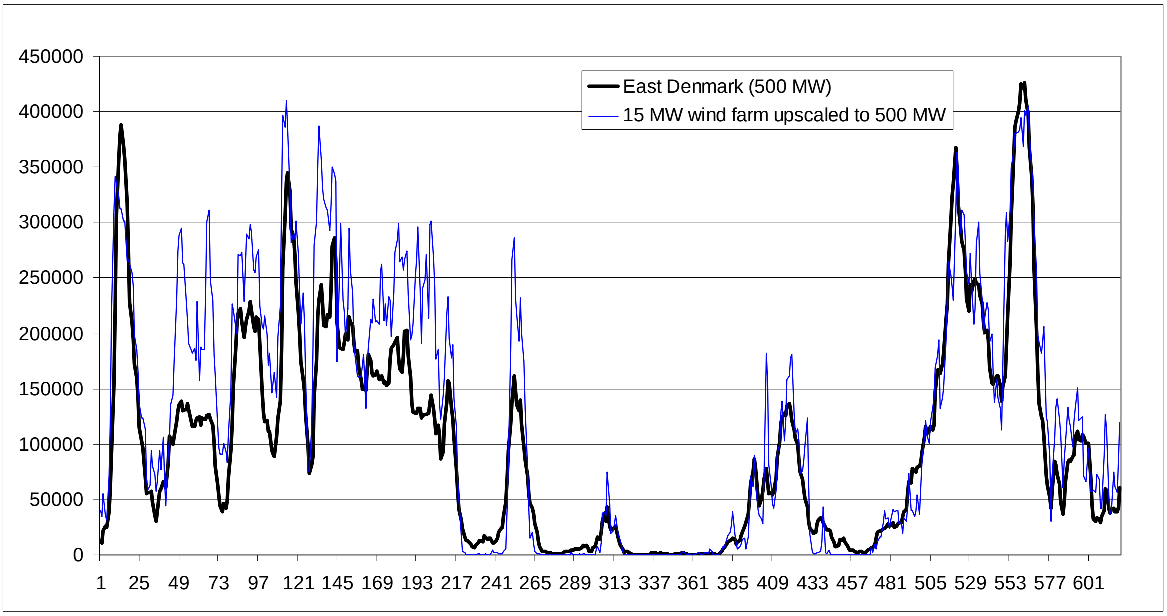


Figure 3. An example of wrong upscaling: a single site would see more variations, peaks and calms than dispersed, large scale wind power production (here 500 MW, 200 x 100 km^2).

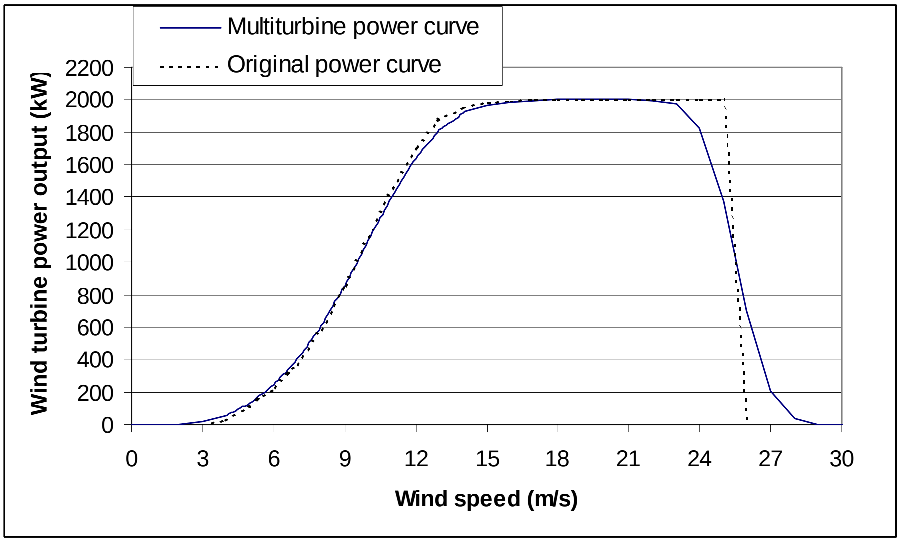


Figure 4. To convert the wind speed time series to wind farm power production, a multiturbine power curve was used, smoothing out the production near the cut-in (3 m/s) and cut out (25 m/s) wind speeds compared with a single turbine power curve.

Data handling principles

For wind power production time series in Finland, Sweden and Norway, the available data presented far less than 100 MW of capacity. This means that these time series had to be upscaled more than 10-fold, to make a large scale wind power production time series for the countries. Upscaling the hourly values means upscaling also the hourly variations. Real large scale wind power production would mean that the output would be smoothened out hundreds or thousands of turbines situated in tens or hundreds of sites. An example of the problem is illustrated in Figure 3, from real data in Denmark. Upscaling data from a single site would give us a different kind of hourly time series – more pronounced peaks and variations – than the real, 500 MW data shows. This is why several, geographically dispersed sites were looked for to make the aggregate time series for the countries. Also, data from single wind speed measurement points were smoothed out before using as data for a larger wind farm.

The time series of only few turbines were checked for longer downtimes of turbines. This was done for several sites in Finland, and the one production series for Norway. Upscaling one wind farm data of 2...8 MW to 50...300 MW means that a large amount of turbines would suddenly be unavailable simultaneously for a long period. The technical availability of wind turbines is usually quite high, more than 95 % is reported from Sweden and Germany (Carlstedt, 2003; ISET, 2002). For hundreds of single turbines, on the average only less than 5 % of the turbines will be unavailable at the same time.

There were 2 wind speed series for Finland and one for Sweden. Most of the data for Norway was as wind speed time series. The wind speed was converted to wind power production. First the wind speed was smoothed out by taking a 2-hour-sliding-average for each hour. This smoothened wind speed was converted to power production using an aggregated, multi-turbine power curve, Figure 4 (see also section 4.2).

For single turbine data, the same kind of smoothing was done, by first converting back to wind speed, and then applying the same method as for the wind speed time series (only one site in Finland).

The focus in this study is on the variations of wind power production. Basically the error in the data sets comes from not having tens of aggregated wind farm time series available to represent a combined production of a country. The data handling procedure trying to smooth out some of the variations in a point wind speed measurement data is artificial and will introduce some error to the data sets. The smoothing of the wind speeds, by sliding 2 hour averages, make the most of the reduction of variability. The use of a multiturbine power curve will mostly affect the time series near the cut in wind speeds, above 22 m/s (Figure 4). All in all, as the yearly energy production will remain the same in the time series, this procedure will mainly affect the variability of the production, and the error is considered small. For Finland data set, this procedure was done for 15 % of the data (3 time series representing 150 MW of a total of 1000 MW). For Norway nearly all data was handled this way, so there is probably error involved, however, as described before, compared to the original error of not having enough time series data, this procedure will reduce error, not increase it.

To compare the data sets of different installed capacity, they were represented as relative production, as % of installed capacity. It could be useful to represent the data relative to average power instead of maximum power, installed capacity. However, as the average power is changing from year to year, the nominal power is here chosen as a relative measure:

$$p_i = \frac{P_i}{P_{TOT}} \qquad , \qquad (1)$$

where p_i is the relative production for hour i as % of capacity, P_i is the production MWh/h for hour i and P_{TOT} is the installed capacity.

2.2 Data set for Norway

For Norway, wind power production data was acquired from one site. However, the data had missing periods especially for year 2001. Two wind speed measurement time series were acquired from potential wind power sites in Middle and South Norway, covering parts of years 1999 and 2000.

Norwegian meteorological institute (NMI) data was well representative for wind power production: it is measured hourly and with high average wind speeds. 5 sites along the coastline were used for 2000 and 11 sites for year 2001.

Norway is the largest country when considering the largest dimensions between the potential wind farm sites: about 1400 km North-South and 700 km West-East. The South Norway area is about 500 km North-South and 150 km West-East, Middle Norway 300 and 100 km, and North Norway 400 and 400 km respectively.

For up-scaling, Norway was divided to 3 regions, first aggregating the available data as simple averages per site for each region South, Middle and North Norway. The total wind power production was also a simple average: same amount of wind power was assumed to South, Middle and North Norway.

In Norway data, there were several periods of high wind speeds above the cut out wind speed of wind turbines (Figure 4). Especially during the first months of 2000 (7.- 8.1., 3.-4.2.,10.-11.2.) and November, 2001 (3.11. and 10.-11.11.), and first months of 2002 (10.1., 16.2.).

2.3 Data set for Sweden

For Sweden, wind power production data was acquired from 2 sites in Southern Sweden (West and South coast), 2 sites in Middle Sweden (by the large inner lake and on the island of Gotland East coast) and one site in Northern Sweden by the East coast. From the Northern part, also one wind speed measurement time series was acquired (SMHI, 2003). The maximum distance between the wind power data sites in South Sweden area is about 300 km North-South and 400 km West-East, in Middle Sweden 300 km West-

East, 200 km North-South and in North Sweden 200 km in both ways. The maximum North-South dimension for the wind data sites in Sweden is 1300 km.

For upscaling, a 1000 MW wind power production series was produced, representing the geographic distribution of potential wind power production in Sweden. Most of the capacity was assumed in Southern Sweden regions, with 400 MW West/South coast and 400 MW inner lake/Gotland island. 200 MW was assumed in Northern Sweden.

2.4 Data set for Finland

Even though the amount of wind power in Finland is still modest (41 MW at the end of 2002), the capacity installed is well spread along the long coastline and Lapland fells. As a courtesy of 10 wind power producers, and 2 power companies with wind speed measurements in high masts, wind power production data was available from a total of 55 turbines on 21 sites and wind speed data was available from 2 sites (in the internet, only Lumituuli, 2003). The data is presented in Table 1 and Figure 5.

The maximum distance between the sites is 1000 km North-South and 400 km West-East.

As the data was used to represent large scale wind power production, it was upscaled. For this upscaling, first a 1000 MW wind power production series was produced, so that it would represent the geographic distribution of a potential wind power production in Finland: Lapland and Åland archipelago and the Southern coast were reduced to a tenth of large scale capacity each, and the West coast was given the bulk of wind power production (300 MW in the South and 400 MW in the North of West coast). Upscaling is presented in Table 1.

From the wind speed data available for Southern part of Finland, some cut-out situations with wind speed exceeding 25 m/s were found: 29…30.1.2000; 1. and 15.11.2001 and 25.1.2002.

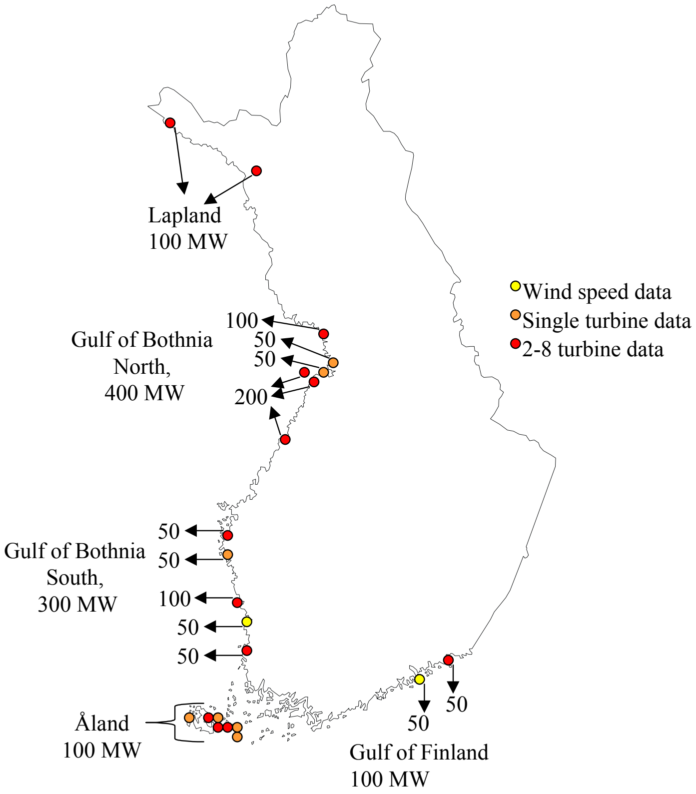


Figure 5. Time series collected for wind power production in Finland.

Table 1. Wind power production data from Finland, and upscaling to 1000 MW wind power.

Site (region)	Turbines /wind speed	Data MW	Upscaled to
Kotka (South coast, East)	2 x 1 MW	2.0 MW	50 MW
Loviisa (South coast, East)	Hourly wind speed 100 m.a.g.l	2.0 MW	50 MW
Åland archipelago (South coast, West)	12 turbines on 7 sites (80 km): 225 kW Sottunga island, 500 kW Eckerö, 500 kW Kökar island, 4 x 600 kW Lemland, 2 x 500 kW+600 kW Finström, 500 kW Vårdö island, 600 kW Föglö island	6.32 MW	100 MW
Uusikaupunki (West cst, South)	2 x 1.3 MW	2.6 MW	50 MW
Eurajoki (West coast, South)	Hourly wind speed 100 m.a.g.l	2.0 MW	50 MW
Pori (West coast, South)	8 x 1 MW	8.0 MW	100 MW
Närpiö (West coast, South)	1 x 750 kW	0.75 MW	50 MW
Korsnäs (West coast, South)	4 x 200 kW	0.8 MW	50 MW
Kalajoki, Siikajoki, Hailuoto (West coast, North)	10 turbines on 4 sites (100 km): 2 x 300 kW Kalajoki, 2 x 300 kW and 2 x 600 kW Siikajoki (2 sites), 2 x 300 kW + 2 x 500 kW Hailuoto	4 MW	200 MW
Lumijoki (West coast, North)	1 x 660 kW	0.66 MW	50 MW
Oulunsalo (West coast, North)	1 x 1.3 MW	1.3 MW	50 MW
Kuivaniemi (West coast, North)	6 x 750 kW	3 MW	100 MW
Lapland	8 turbines on 2 sites (100 km): 5 x 600 kW Olos, 2 x 450 kW + 600 kW Lammasoaivi	4.5 MW	100 MW
TOTAL	55 turbines on 21 sites + 2 wind speed measurement sites	38 MW	1000 MW

2.5 Data set for Denmark

For Denmark, the system operators Eltra (West DK) and Elkraft System (East DK) have hourly production data available at their internet sites, starting from year 2000 (Eltra, 2003; Elkraft, 2003). The maximum distance between the sites in West Denmark is roughly 300 km North-South and 200 km West-East. For the Eastern part, the dimension is about 200 km North-South and 100 km West-East. Bornholm island, South of Sweden, is a part of East Denmark.

Danish data is representing the realised production of thousands of turbines and hundreds of sites. However, there has been a significant increase in wind power capacity during the two years: from 1730 MW in start of 2000 to 2612 MW at the end of year 2002 (West Denmark: 1340 MW in the start of 2000, 1790 MW in the start of 2001, 1970 MW in the start of 2002 and 2040 MW in the start of 2003. East Denmark 390, 503, 554 and 572 MW respectively).

To be correct in converting the hourly production in MWh/h to relative production, as % of capacity, exact data on each wind farm's network connection would be needed. This means making an hourly P_{TOT} time series in formula 1, P_{TOTi}. If the information on capacity addition (or reduction as some old wind turbines have been taken from operation) was not correct, a step up in the MW time series at a wrong hour could distort the real production time series. This would either add more variations or damp the real variations from one hour to the next.

Daily data on capacity development in East Denmark was obtained for years 2001-02. For West Denmark, and for year 2000 of East Denmark, no exact data on capacity was available. For these data sets, an approximate hourly MW series has been constructed to convert the data to % of capacity. For West Denmark, the capacity has been rising at an average rate of 50 kW/hour in 2000 and 13 kW/hour in January 2001, after which a constant capacity has been used, until a rise in November/December 2002 of 48 kW/hour. The large offshore wind farm in Horns Rev was started in December, 2002. However, due to the low availability during the first testing period, this 160 MW was not taken as increase in the installed capacity. For East Denmark, the capacity has been rising at an average rate of 16 kW/hour in 2000. The maximum rise of capacity, in the daily capacity data of East Denmark, is 17.8 MW in 2001 and 11.5 MW in 2002.

Looking at the capacity increase in Denmark (Elkraft, 2003; Eltra, 2003), it has been quite linear. The error made here would stay below 20 MW at any hour (the difference between the approximation used here and the real life). The errors for the hourly variations are even smaller, as the capacity increase in practise comes as 1-3 turbines at a time, when the test operation of a wind farms starts. Assuming a maximum 10 MW instantaneous capacity increase in an hour, this would be seen as a 0.5 % of capacity error in the hourly variation, either overestimating an upward variation or underestimating a downward variation in the data set used in this study. The error is very small in the situation where there is in real life no increase in the capacity from one hour to the next – an assumed 60 kW increase in capacity is 0.003 % of the total capacity in the beginning of year 2000 and 0.002 % at the end of year 2002.

The advantage of the procedure used here is that we get a better knowledge of how much, as % of capacity, the production has been.

2.6 Long term yearly production data

Long term data was used to determine the representativeness of the wind resource for the example years.

Yearly wind production index data was acquired from existing national wind energy statistics (Laakso, 2003; Carlsted, 2003 and Naturlig energi, 2003). Production index data was used because the yearly wind production data (also available from statistics) needs to be corrected for the capacity built during the year. As exact average capacity is not known, but only the capacity in the beginning and end of years, this would result in errors trying to make a representative and comparable figure for the yearly production. Also, the wind index data reaches farther back in time than the production data, which has only started in the 90's for Finland and late 80's for Sweden and Denmark. Norway wind index data does not yet exist.

Wind power production index is a measure of one year's production compared with the long term average production. For Denmark and Sweden, this is derived by looking at the production of reference turbines, operating since the end of 1980's. Production index for one year is the production of those turbines that year divided by the average production of those turbines over a long reference time period. Index of 100 % means that the production during the year has been the same as for long term average. For Finland, the production indices are calculated from the Finnish Meteorological Institute (FMI) wind speed measurements along the coast, converting the wind speed to power production. In Finland, the coastal areas South and West experience somewhat different wind resource variations, that is why the production indices are presented for 4 sites (Laakso, 2003). The long term average period is 15 years, 1987-2001, over which period the wind index is on the average 100 %.

If further work in comparing the example years 2000-02 with long term wind resource is needed, the Reanalysis wind speed data (6-hourly) can be used (NCEP/NCAR, 2003).

3 Large scale wind power production

In this chapter, a closer look on the wind power production in the Nordic countries during the example years 2000-2002 is taken. The patterns of wind power production are analysed, to see how the aggregation of production from a larger area affects these patterns. The smoothing effect can be seen from most of the statistical analyses presented in this chapter. The representativeness of the data sets and the example years are discussed in section 3.9.

Examples of the data sets in this study are presented in Figure 6 for February, 2000. Plots of yearly data for years 2000 and 2001, for the 4 countries and their combination, is presented in Appendix.

When studying the effects of wind power on power systems, the wind power data has to represent large scale wind power production - from hundreds (or thousands) of turbines, tens (or hundreds) of sites. Geographical spreading of production evens out the total production from an area. Duration of calms will be substantially decreased, as the wind blows almost always at some part of the system area (Giebel, 2001). Maximum production level will not reach installed nominal capacity, as the wind will not blow as strongly at all sites simultaneously, and of hundreds or thousands of WTs not all are technically available at each instant. The extent of the smoothing effect of wind power production depends mainly on number of sites and distribution of sites over the area, as well as spatial correlation between the production of the sites (Focken et al, 2001).

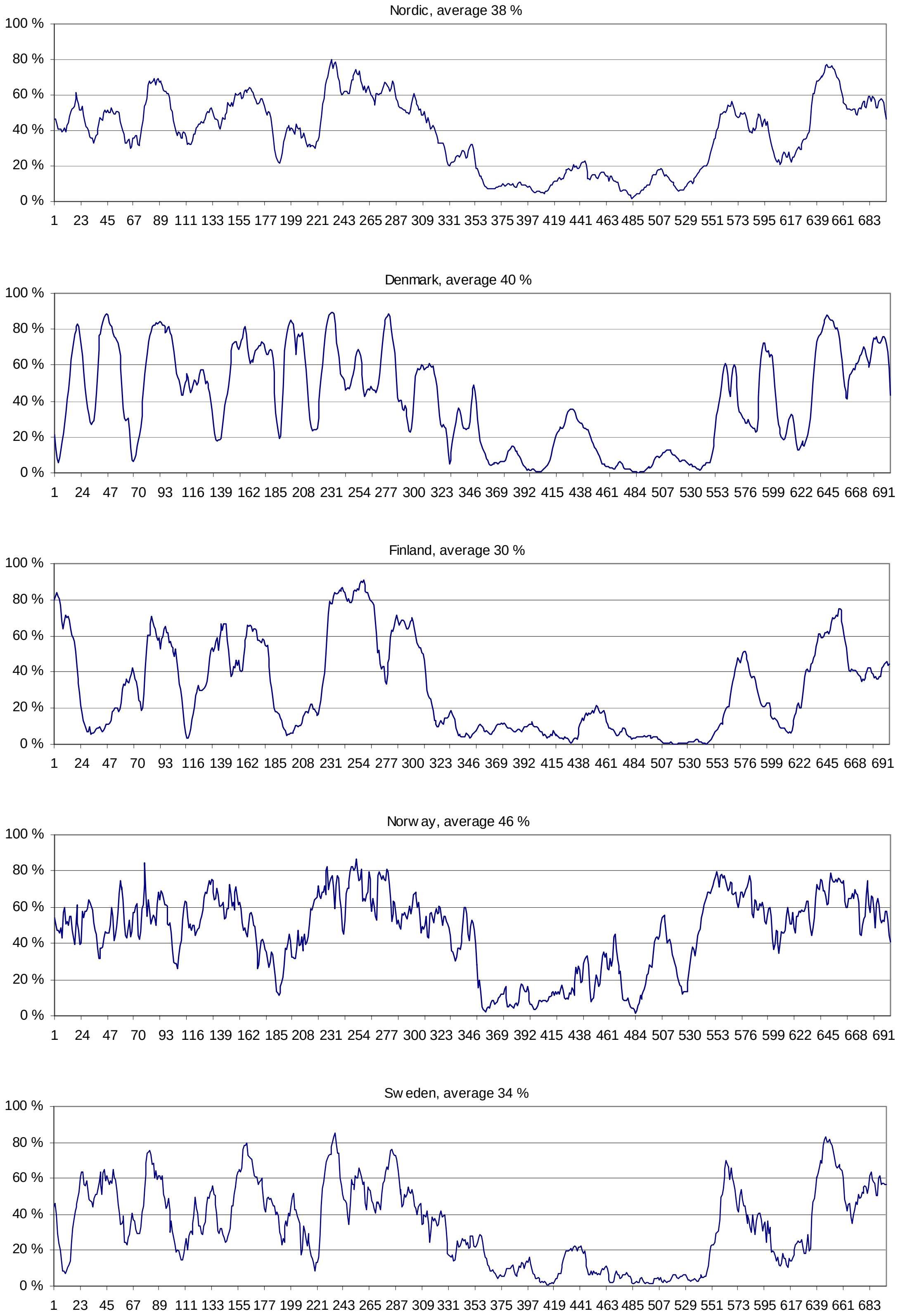


Figure 6: Hourly wind power production in February 2000. The production is as % of installed capacity (y-axis). The average production during the month is denoted above the curve.

Basic statistics of the wind power production data used

The average production from all seasons in the study period is shown in Table 2. The 12 months are divided into seasons as the following: spring is March, April and May; summer is June, July and August; autumn is September, October and November; winter is January, February and December.

First of all, the difference in wind resource is notable: Norway has an excellent wind resource, with average production of 32 % of capacity compared with 22–24 % for the other Nordic countries. Denmark has here the lowest production rates, as % of capacity. This is probably due to the data containing also sites in the inland and sites with older turbines with 20-40 m towers: the rotors are not reaching as good wind resource as the new, 60-100 m high MW scale turbines. The production in 2000-02 does not yet have large offshore wind power included, with better wind resource (2 x 160 MW wind farms erected in late 2002 and 2003).

It can be seen from Table 2, that year 2000 was considerably more windy than years 2001-02, except for Sweden where year 2002 was as good as year 2000. The production during the summer months is 60–80 % of the yearly average and production during the winter months is 110–150 % of the yearly average (Table 2).

The basic statistics of the yearly time series are presented in Table 3. Wind power production from the 4 countries and the combination are shown. As a comparison, data from one site is shown. To take a closer look at the regional wind power production, the same statistics are presented in Table 4, for the regions of the countries (Denmark 2 regions; Norway and Sweden 3 regions and Finland 4 regions). For the regions, there is clearly not as good smoothing effect seen, except for the real data for Denmark East and West.

Table 2. Average wind power production in the Nordic countries in the study period. Wind power production is presented as relative production, % of installed capacity.

	Nordic	Norway	Denmark	Sweden	Finland
Years 2000-2002	25.1 %	32.3 %	22.2 %	23.5 %	22.3 %
Year 2000	26.6 %	33.8 %	24.1 %	24.0 %	24.6 %
Year 2001	24.1 %	31.4 %	20.3 %	22.5 %	22.2 %
Year 2002	24.5 %	31.8 %	22.0 %	24.0 %	20.2 %
Winter 2000	34.9 %	45.0 %	33.5 %	31.8 %	29.3 %
Spring 2000	25.6 %	33.2 %	20.8 %	21.5 %	26.8 %
Summer 2000	18.0 %	21.4 %	17.7 %	16.2 %	16.6 %
Autumn 2000	28.1 %	35.6 %	24.6 %	26.5 %	25.8 %
Winter 2001	28.7 %	41.8 %	22.0 %	27.5 %	23.7 %
Spring 2001	20.5 %	24.7 %	18.9 %	18.5 %	19.9 %
Summer 2001	18.1 %	21.9 %	15.4 %	16.5 %	18.6 %
Autumn 2001	29.2 %	37.7 %	25.1 %	27.6 %	26.6 %
Winter 2002	35.0 %	45.0 %	32.9 %	34.1 %	28.1 %
Spring 2002	23.7 %	30.8 %	20.6 %	23.0 %	20.5 %
Summer 2002	16.7 %	20.5 %	16.6 %	16.8 %	13.0 %
Autumn 2002	22.9 %	31.2 %	18.2 %	22.5 %	19.5 %

Table 3. Descriptive statistics of hourly wind power production in the Nordic countries for years 2000-2002. Wind power production is presented as relative production, % of installed capacity. The width of the areas are presented as largest distance (km) North-South and West-East.

	Single site	**Denmark**	**Finland**	**Norway**	**Sweden**	**Nordic**
Largest distance NS-WE	-	300-300	1000-400	1400-700	1300-400	1700-1100
Mean	25.9 %	22.2 %	22.3 %	32.3 %	23.5 %	25.1 %
Median	14.9 %	14.6 %	17.5 %	29.2 %	18.6 %	22.4 %
Standard Deviation	28.2 %	21.2 %	17.6 %	19.6 %	18.3 %	14.5 %
Range	105.0 %	92.7 %	91.1 %	93.0 %	95.0 %	85.4 %
Minimum	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	1.2 %
Maximum	105.0 %	92.7 %	91.1 %	93.1 %	95.0 %	86.5 %

The median is the value in the middle, when sorting all the values in an increasing or decreasing order. For wind power production it is typical that median is lower than the mean value. Most of the time, the production is less than average. When aggregating production from a larger area, the median gets closer to the mean value.

The smoothing effect can be seen in the range of the production, the maximum and minimum encountered during the years. For the total Nordic time series the production never goes to 0, however, the lowest production is only 1 % of installed capacity. For one country, the production can go to 0. The maximum production from geographically dispersed wind power production stays below 90 % of capacity for the Nordic countries.

For a single country, it is below 95 % of capacity. Even if we are talking about large scale wind power production, the production range will still be large compared with other production forms: maximum production will be 3–4 times the average production, depending on the area (Table 3; Giebel, 2000).

Another trend of smoothing can be seen in the standard deviation values. Standard deviation tells about the variability of the hourly time series, it is the average deviation from mean value:

$$\sigma = \frac{\sqrt{n\Sigma x^2 - (\Sigma x)^2}}{n(n-1)} \qquad (2)$$

The reduction in variability (the reduction in standard deviation) is depicted in Figure 7.

For a single turbine, the standard deviation is close to 30 % of capacity, somewhat larger than the mean. For a country, the standard deviation gets closer to 20 % of capacity, for a

Table 4. Descriptive statistics of hourly wind power production in the different regions of Nordic countries. Years 2000-2002.

	South Norway	Middle Norway	North Norway	DK East	DK West	South Sweden	Middle Sweden	North Sweden	FI South coast	FI West coast South	FI West coast North	FI Lapland
NS-WE	500-150	300-100	400-400	200-100	300-200	300-400	300-200	200-200	50-80	250-30	150-50	100-100
Mean	30.9 %	38.2 %	28.0 %	21.0 %	22.5 %	25.4 %	21.2 %	24.3 %	23.0 %	22.5 %	22.4 %	20.3 %
Median	26.1 %	29.0 %	22.7 %	12.8 %	14.9 %	16.8 %	12.9 %	16.0 %	16.5 %	15.4 %	13.7 %	13.4 %
StDev	24.5 %	33.3 %	22.8 %	21.8 %	21.7 %	24.5 %	22.2 %	23.7 %	20.8 %	21.4 %	23.8 %	20.3 %
Range	100.0 %	100.0 %	100.0 %	92.5 %	94.0 %	100.6 %	98.8 %	103.9 %	99.4 %	99.4 %	102.5 %	98.4 %
Minimum	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	-0.1 %	0.0 %	0.0 %	-0.1 %	-0.1 %	-0.3 %	0.0 %
Max	100.0 %	100.0 %	100.0 %	92.5 %	94.0 %	100.5 %	98.8 %	103.9 %	99.3 %	99.3 %	102.2 %	98.4 %

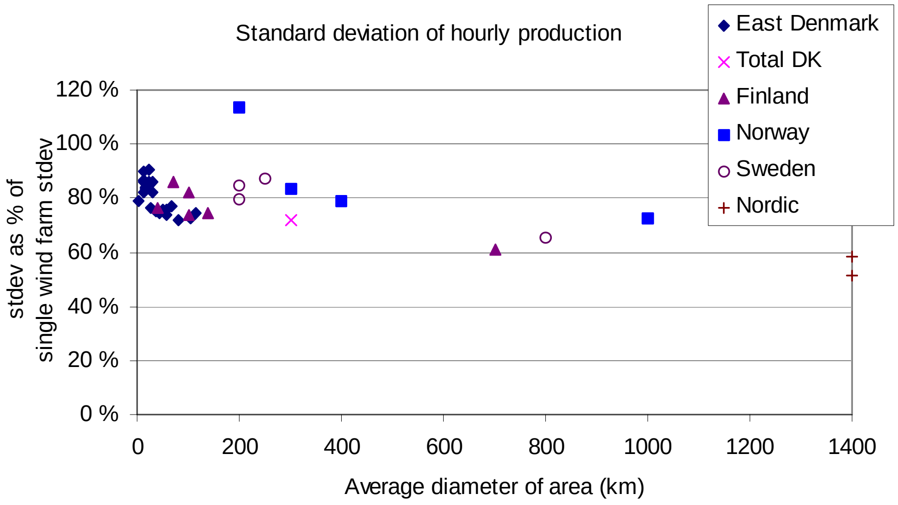


Figure 7. Reduction in variability of wind power production: reduction in standard deviation of hourly time series taken from different areas, as relative to a single site standard deviation (28 % of capacity). Data from year 2001.

larger country like Norway, Sweden and Finland, where the sites are spread 1000 km apart, the standard deviation is less than 20 % of capacity. For the total Nordic time series, the standard deviation is below 15 % of capacity (Table 3). In Figure 7 it can be seen that Denmark, Finland and Nordic data represent a reduction, whereas specifically the Norwegian data series shows far more variations than those of considerably smaller East Denmark. This was as expected, as the Norwegian data for the areas consists of 2–5 time series only. For the Nordic data, also a data set where wind power was concentrated in Denmark (half of the capacity) was made, and there the reduction in standard deviation is to 60 % of the single site value, compared with the nearly to 50 % for an evenly distributed wind power production (Figure 7).

3.2 Frequency distributions of wind power production

To take closer look at wind power production, the hourly production of years 2000 and 2001 are plotted as frequency distributions. In Figure 9 the data is grouped with the scale in x axis as following: 0 means the number of values below or equal to 0 ; 5 % means the number of values above 0 and below or equal to 5 % etc.

It can be seen in Figure 9, that large scale production of wind power means shifting the most frequent ranges to the middle of the graph. For the single site, the production is almost half of the time below 10 % of capacity. For the wind power scattered to all Nordic countries, the production is most of the time in between 5...40 % of capacity, and is seldom below 5 % or above 70 % of capacity.

The probability of wind power production can also be presented as a duration curve. The duration curve of power production is often used in the energy sector to illustrate the time the power plant produces a certain power level. In Figure 8, the Nordic wind power production for year 2000 is shown chronologically (the varying curve) and as a duration curve, where the production values are sorted in descending order before drawing the curve. The duration curve does not tell about the correlation between consecutive values, for this a persistence study is made separately in section 3.5.

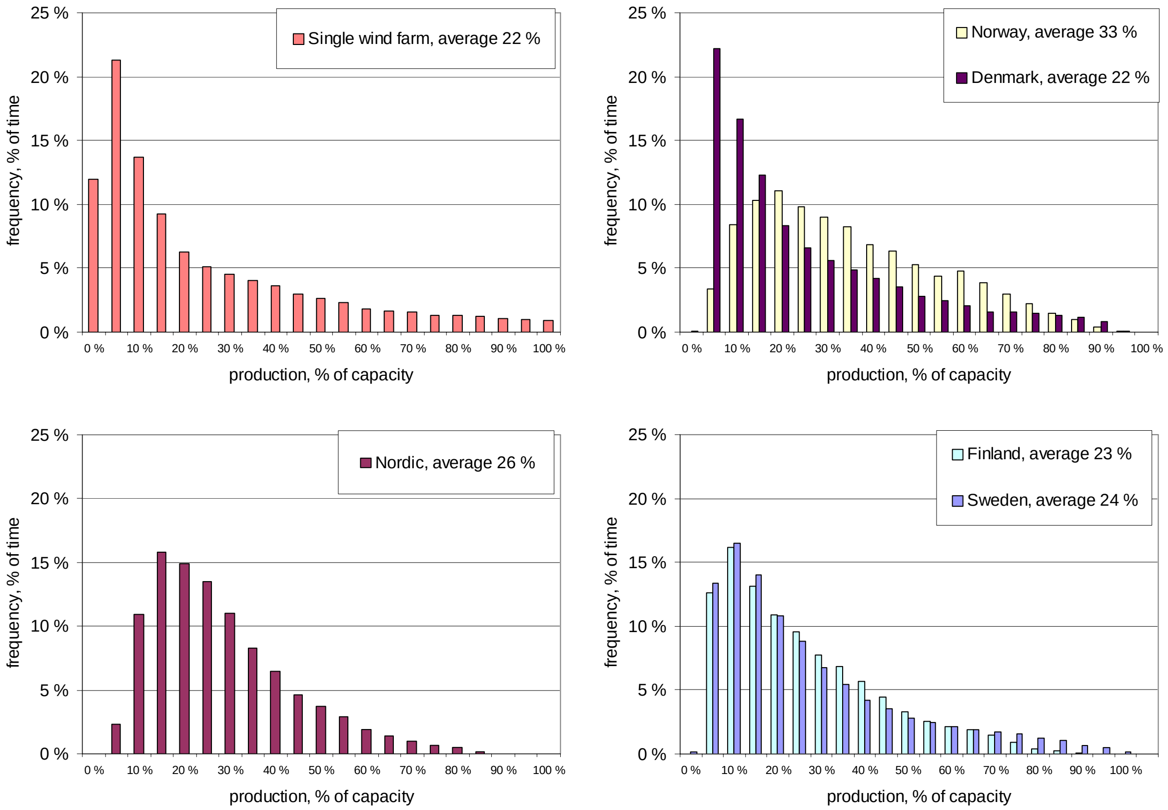


Figure 9. Frequency distribution of wind power production from one site, from a country and for a theoretical total Nordic production. Example years 2000 and 2001. The production values at x axis note the upper value of the range.

In Figure 10, the smoothing effect is presented as duration curves. The duration curves for the countries are presented in Figure 11. Here again it can be seen that the Norwegian wind power production is at a higher level than for the other countries, and also the smoothing effect is stronger. The Danish wind power production shows less smoothing effect than the data sets for the other countries. This is due to Denmark being far smaller area than the other countries.

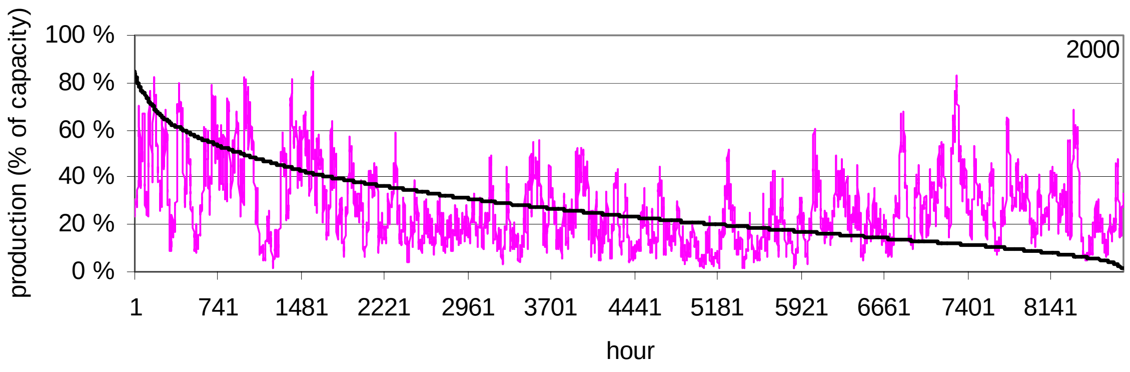


Figure 8 Example of data for this study: the total Nordic wind power production, as a chronological time series and as a duration curve.

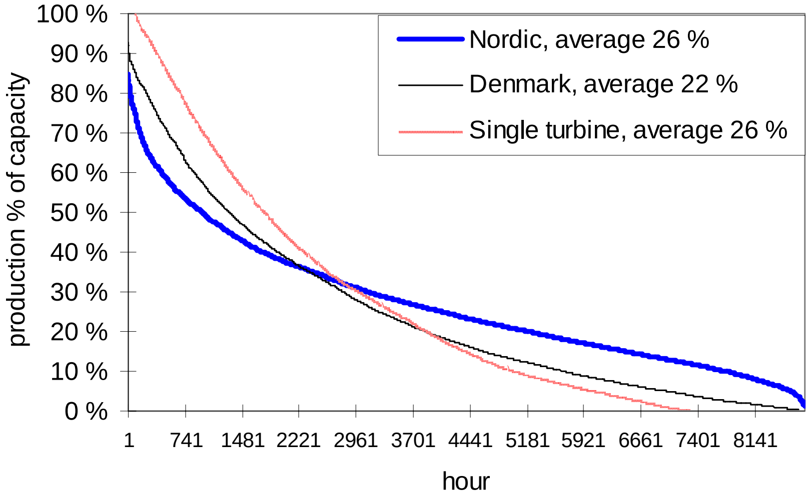


Figure 10. The effect of geographical spreading is to flatten the duration curve of wind power production. Example of year 2000 hourly data, where wind energy distributed to all 4 Nordic countries is compared with one of the wind farms and one of the countries (Denmark). Average production for the curves is denoted in the legend text.

3.3 Seasonal variation of wind power production

In Central and Northern Europe, there is a distinct seasonal variation in wind power production: more production in winter than in summer. For example in the Nordic countries, 60–70% of yearly production comes during 6 winter months (Figure 13). The production during the winter months is 110–140 % of the yearly average and production during the summer months 60–80 % of the yearly average (Table 2). This is also reflected in the range of production values, for example, the hourly data for Nordic countries for these example years 2000 and 2002 ranges between 1...61 % in the summer and 2...85 % in the winter.

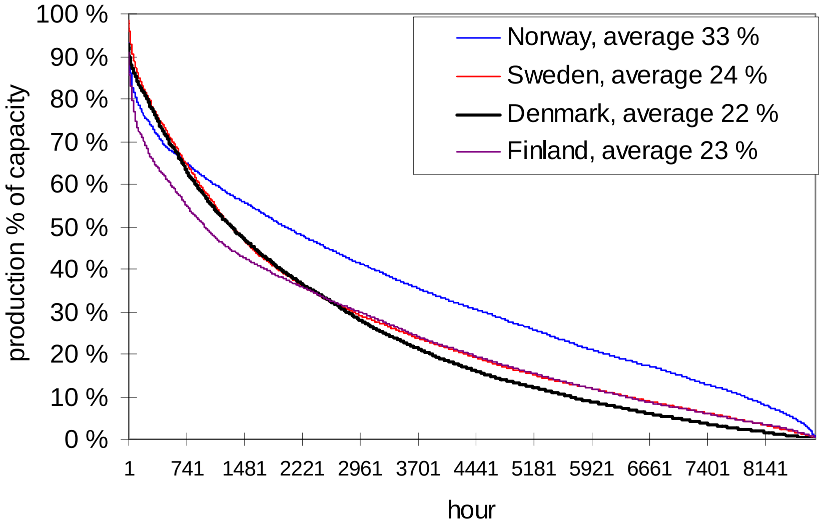


Figure 11. Duration curves for the wind power production in the 4 Nordic countries, year 2000 data. Average production is denoted in the legend text.

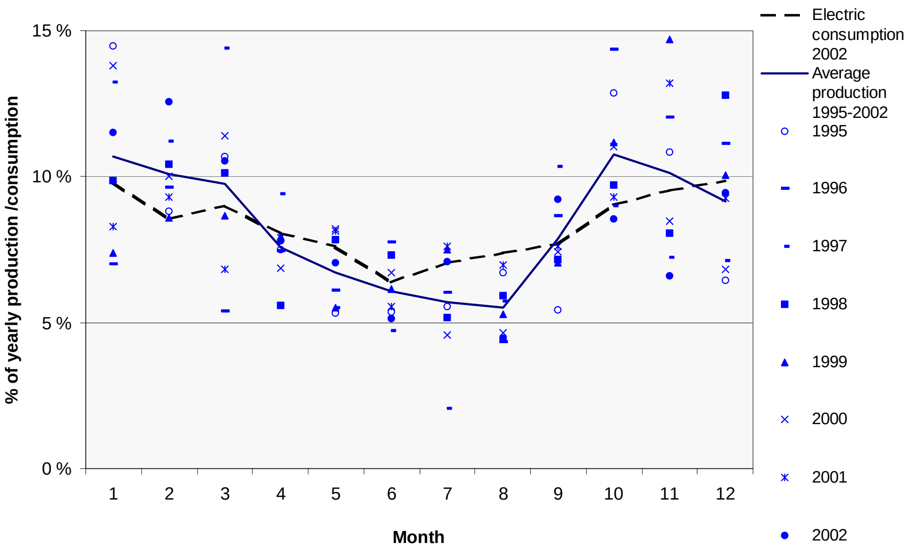


Figure 13. Seasonal variation of total wind power production in Finland in 1997-2001. Average of 1992-2001 is shown (line) together with the electric consumption (dotted line).

Frequency distributions for the 4 seasons are presented in Figure 12. Duration curves for summer and winter are presented in Figure 14 for Denmark and the combined Nordic wind power production.

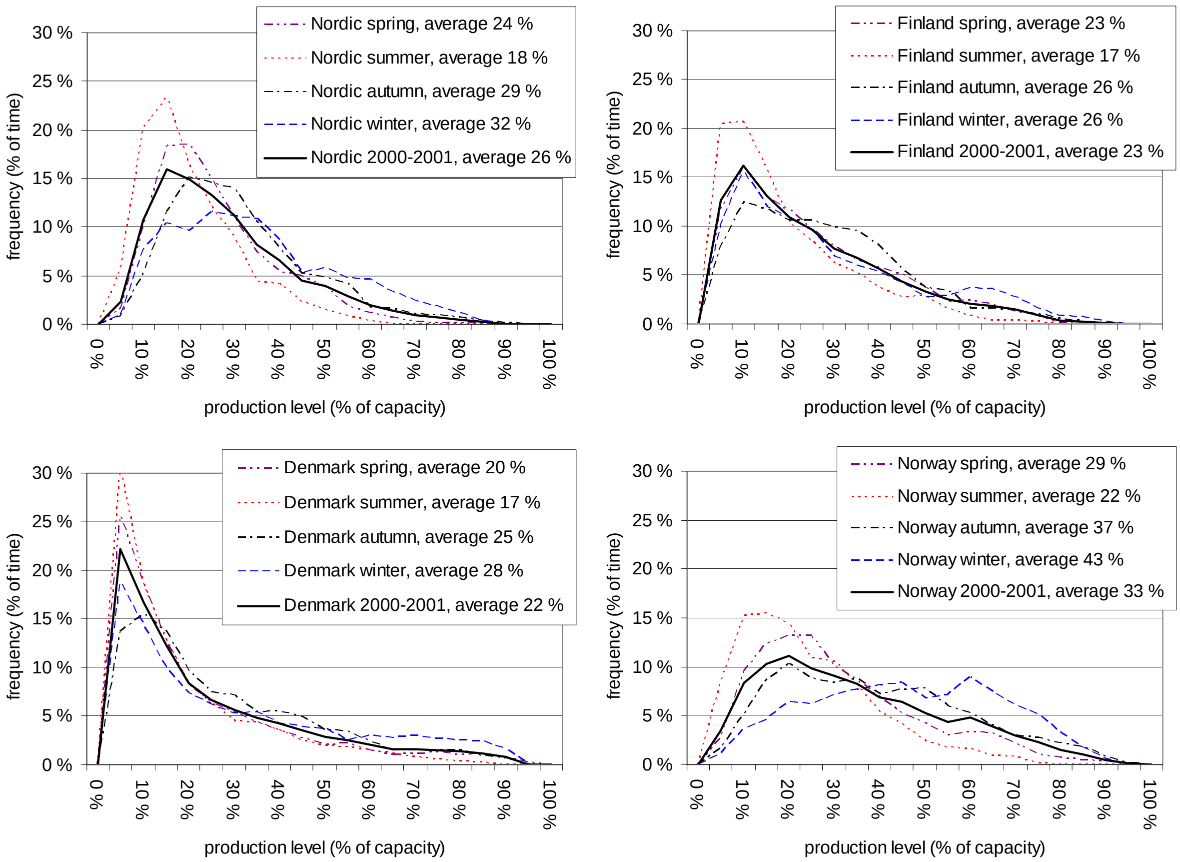


Figure 12. Difference in frequency distributions of wind power production for seasons: the lower production rates have a higher probability in summer, and higher production rates are more probable in winter.Average production during the seasons is denoted in the legend text.

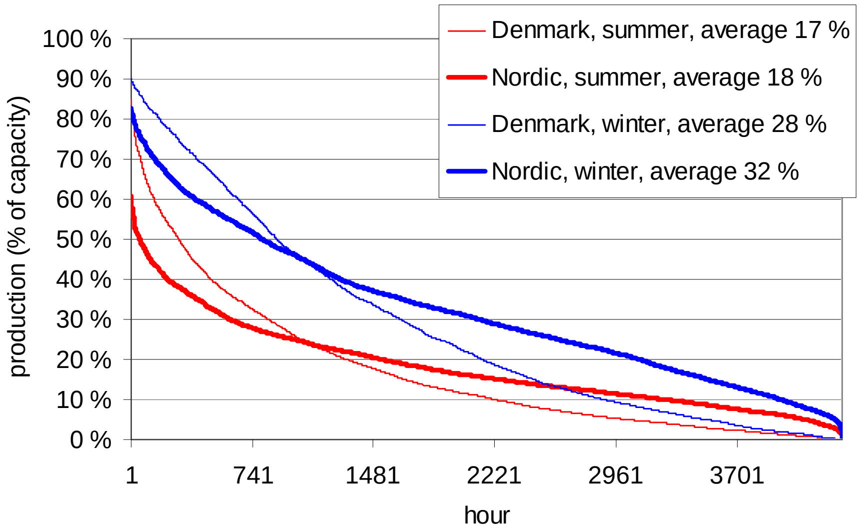


Figure 14. The wind power production is higher during the 3 winter months (upper curves: January, February and December) than the 3 summer months (lower curves: June, July, August). Duration curves for production in 2000 and 2001.

3.4 Diurnal variation of wind power production

Wind is driven by weather fronts and a daily pattern caused by the sun, so depending whether one of these dominates there is either significant or hardly any diurnal pattern in the production. Diurnal variation can also be due to local phenomena, for example in California passes there are morning and evening peaks when wind blows to and from the desert and the sea. In Europe, there is a tendency for winds starting to blow in the morning and calming down in the evening (Ireland: Hurley and Watson, 2002; Germany: Ensslin et al, 2000). In Northern Europe this is mostly pronounced during the summer (Figure 16).

In winter there is not a clear diurnal variation to be seen, except for slightly in Denmark (the uppermost curves in Figure 16 graphs). In summer, the average production at 11…18 hours is on the average above 20 % of capacity compared with less than 15 % of capacity during the night. Wind power production in Denmark and Sweden experience a more pronounced diurnal variation, whereas the sites in the northern part of Finland,

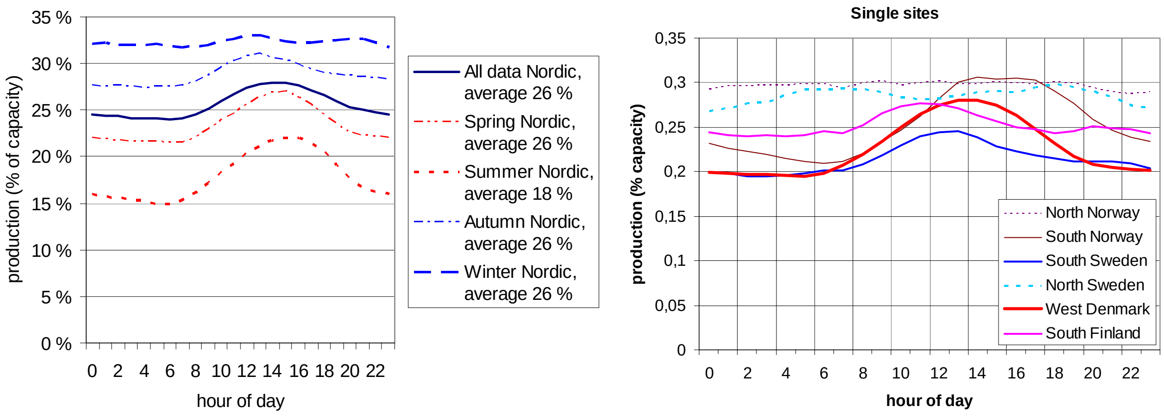


Figure 15. Diurnal variation of wind power production for some example sites. For North Norway, Sweden and Finland, the diurnal variation is practically non existent also for summertime.

Sweden and Norway do not experience any detectable diurnal variation.

The diurnal variation here is presented in Central Europe time, as is used in Denmark, Norway and Sweden. The hours have a shift for summer time in the spring and back to normal time in the autumn (Figure 16). For the single sites with whole year data, the hours are in normal time. A shift in the peak can be seen for the single site data in Figure 15, where data for all countries are in the same graph. The sun rises from the East, warming up Finland first (peak at 10-12 Central Europe time, 11-13 Finnish time), Sweden next (peak at 11-13), Denmark (peak at 13-15) and lastly Norway (peak at 14-17). For Norwegian data, the smoothing made to single wind speed series to represent wind farm data, makes the peak shift somewhat to later than it should be (2-hour-sliding average of wind speeds was done).

3.5 Persistence of wind power production

Frequency distributions and duration curves give some idea of how often certain production levels occur. However, for a varying power production like wind power, also persistence in different production levels is of interest – how long does a certain production level last?

There are two special cases, presenting the greatest challenges in integration of wind power in the system: duration of calms or low wind power production, as well as occurrence of the peaks, which are specially pronounced in wind power production. This analysis gives also insight into how the example years 2000…2002 differ in this respect.

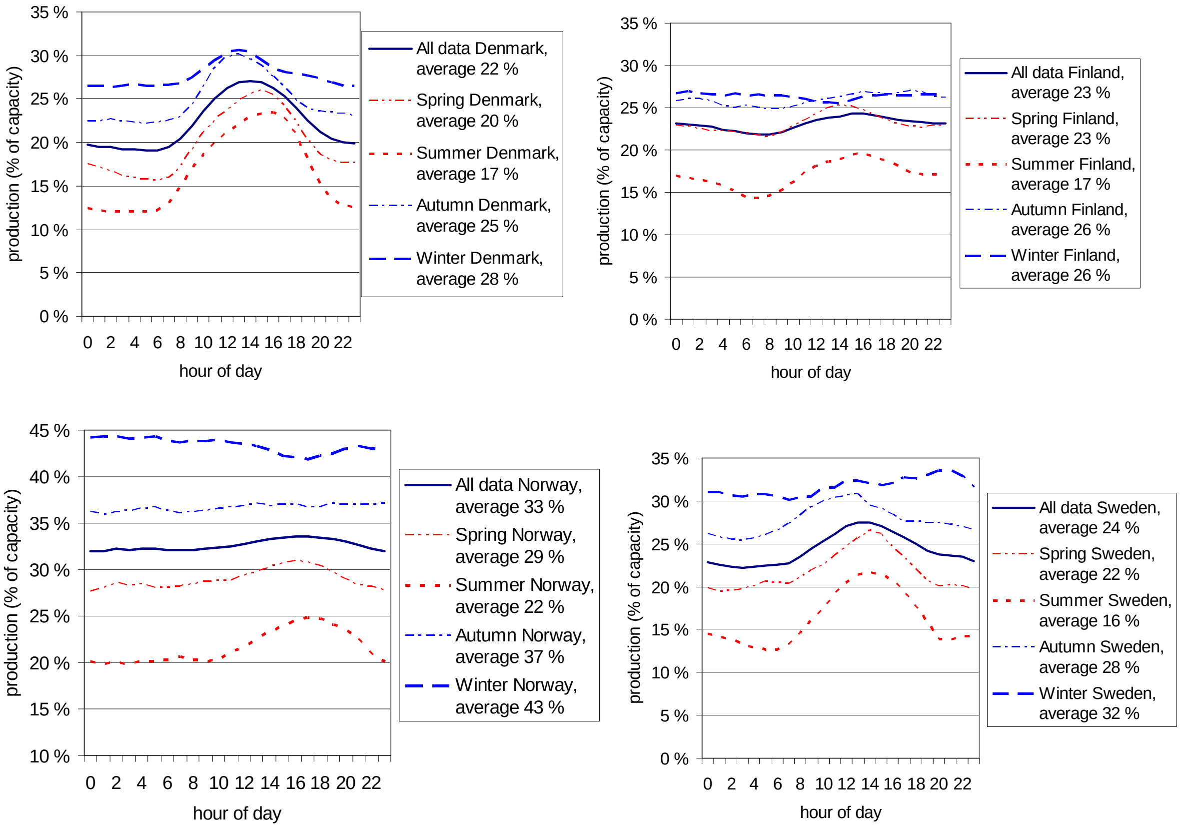


Figure 16. For the Nordic countries, diurnal variation is more pronounced in summer time

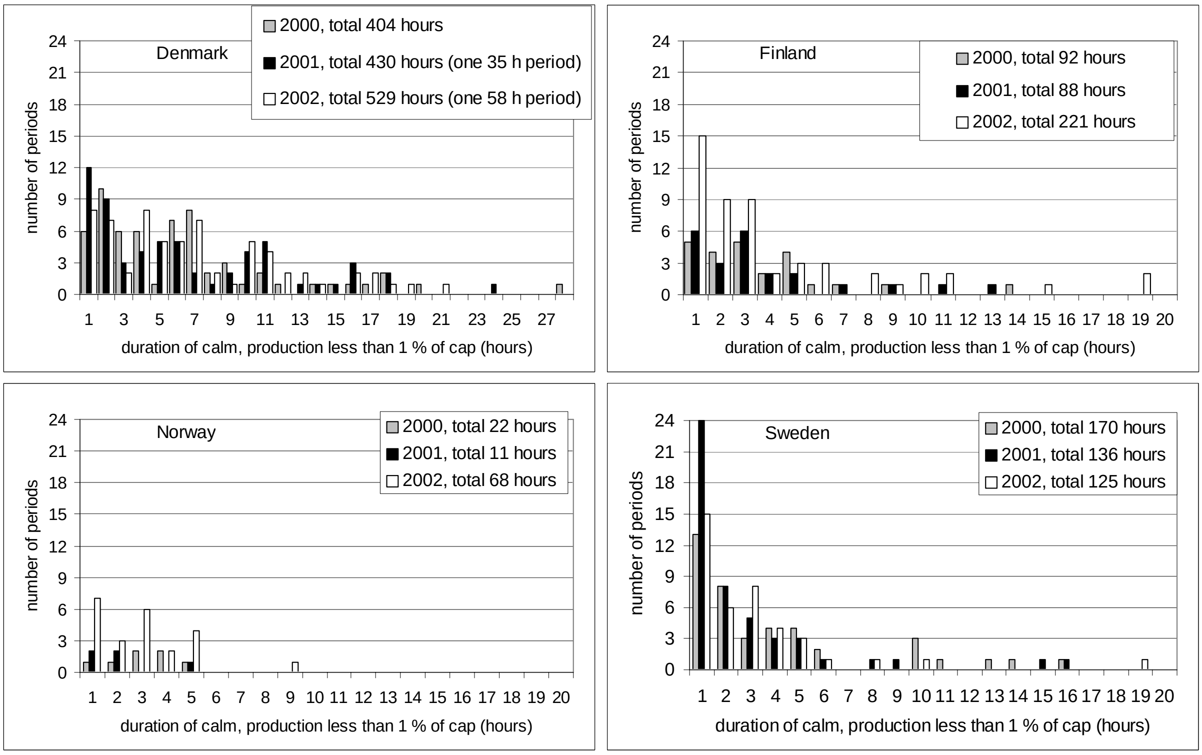


Figure 18. Duration of calms for wind power production, number of different length periods when production below 1 % of capacity. The graphs for countries do not all have the same scale.

Duration of calms

Duration of calms has here been defined as time when wind power production is less than 1 % of capacity. As the average production is of the order of 20–25 % of capacity, this can also be put as about 4–5 % of average production. Additionally low production persistence has been studied: when wind power production is less than 5 % of capacity (roughly 20 % of average production). Production level of 10 % of capacity is already almost half of average production, and wind power production is almost a third of the time below 10 % level (for the total Nordic production, almost 15 % of time, Figure 18). That is why it is not considered as a calm period.

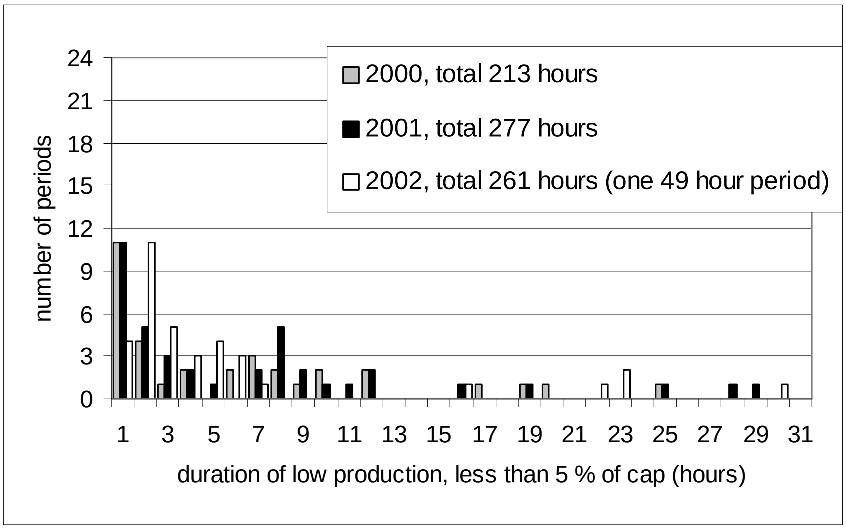


Figure 17.Duration of low production in a total Nordic wind power production, number of different length periods when production less than 5 % of capacity.

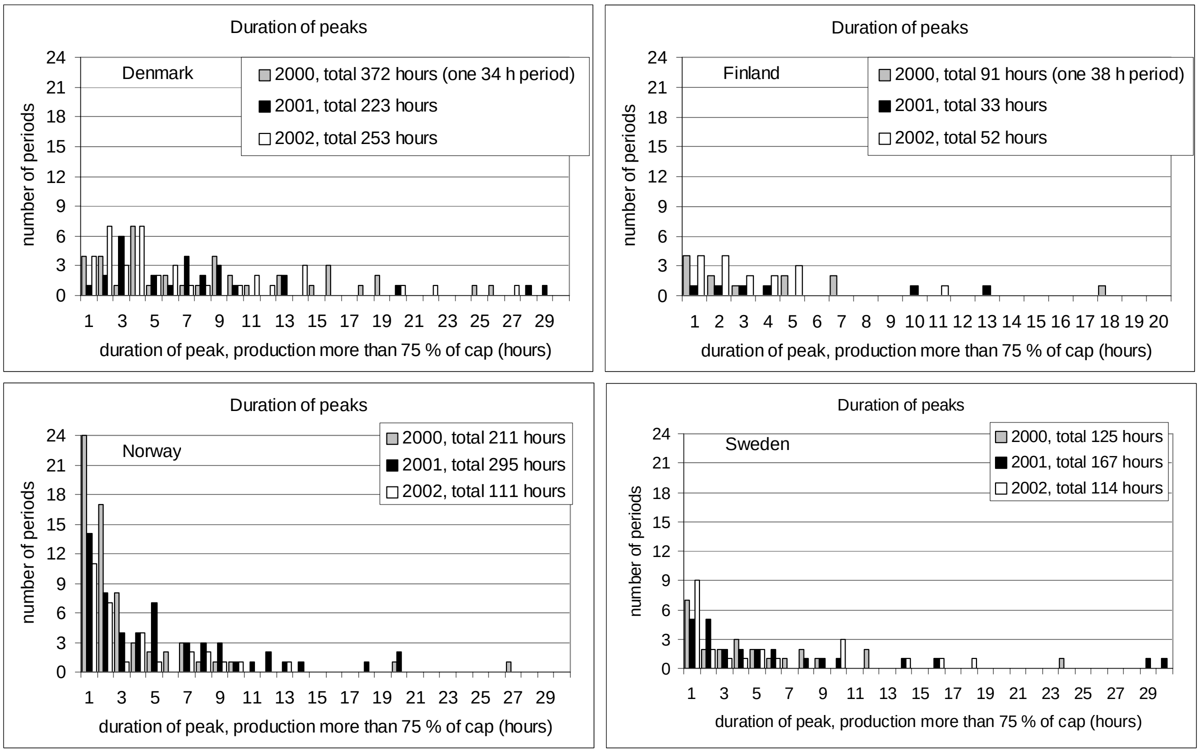


Figure 19. Length of high wind power production periods in example years 2000–2002.

In Denmark, the production was below 1 % of capacity a total of nearly 5 % of time (4.6 – 4.9 – 6.0 % of time in 2000-2001-2002), where as for the larger areas of Finland and Sweden, this was 1–2 % of time. For Norway, the calms were very rare (0.1 – 0.3 – 0.8 % of time in 2000 – 2001 – 2002). The longest duration of calm (production below 1 % of capacity) for Denmark was 58 hours in 2002, 35 hours in 2000. For Finland and Sweden it was 19 hours and for Norway 9 hours. In Figure 18 it can be seen that for Norway, the total amount of hours below 1 % of capacity is half in 2001 compared to 2000, this can be explained by more data series for year 2001. For a total Nordic data set, there were no calms, the production is always above 1 % of capacity. The production was below 5 % of capacity 2–3 % of time (Figure 17).

There are not significantly more and longer calms in year 2001 data than in year 2000 data. This is somewhat surprising: as year 2001 was a lower wind year than year 2000 (Table 2), so intuitively also the calm periods could have been more. In 2002 there were more calms for Denmark and Finland.

The longest duration of low production, less than 5 % of capacity, was 95 hours for Finland and Denmark, and less than 50 hours for Norway, Sweden and the total Nordic time series. The longest periods occurred during spring/summer months (April…August).

The longest duration of production less than 10 % of capacity was 126 h for the total Nordic time series (64 h Norway, 160 h Denmark, 94 h Sweden and 219 h Finland).

Peaks of wind power production

Peak production has here been studied for the level of above 75 % of capacity. As the average production is of the order of 25 % of capacity, this can also be defined as roughly three times the average production.

In 2000, there was one long period with high wind power production exceeding 75 % of capacity: 38 hours in Finland, 34 hours in Denmark, 27 hours in Norway and 24 hours in

Sweden. In addition, there were 1-3 periods of about 20 hours long high production. For the Nordic data, peaks of more than 75 % are rare, none in 2002, 34 hours in 2001 and 84 hours in 2000 with maximum duration of 14 hours.

In Denmark and Finland, there are more and longer periods of peak power production in year 2000 data than in year 2001-02 data. This was as expected, as year 2000 saw a better wind resource (Table 2) so also the high wind periods are supposedly more. For Sweden and Norway, year 2002 data has less peaks than the years 2000-01, but year 2001 had the most peaks.

3.6 Correlation of wind power production

Cross-correlation ($r_{x,y}$) is a measure of how well two time series follow each other. It is near the maximum value 1 if the ups and downs of the production occur simultaneously, near the minimum value –1 if there is a tendency of decreasing production from one site when increasing production at the other site, and close to zero if the two are uncorrelated, and the ups and downs of production do not follow each other at two sites.

$$r_{x,y} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_x)(y_i - \mu_y)}{\sigma_x \sigma_y}, \qquad (3)$$

where μ denotes the average, σ the standard deviation and n the number of points in the time series.

Correlation can also be calculated for a single time series but with time lags. This is called autocorrelation. For wind power production, the autocorrelation decreases soon with increasing time lag, already at 12 hour lag the correlation becomes weak (Pryor & Barthelmie, 2001)

If wind production data is not correlated, there can be strong winds in one place at the same time as weak winds in the other. When distributing wind power production to a larger area, the total production will be smoother and less variable, if the correlation between the sites is low.

The cross-correlations were calculated for all sites in the Nordic countries for one year, 2001 (Table 5), when the data available included most sites, altogether 33 time series. Some of the time series were aggregated production data from a larger area, for which the coordinates were estimated from the centre of the area. The results are presented in Figure 20. The cross-correlation decreases fast at first, r_{xy} =0.7 for distance of about 100 km and 0.5 for distance of about 300 km, after which the decrease is slower.

There is significant variation in the cross correlation coefficients for a similar distance, as is expected. The correlation becomes weak, below 0.5, with distances above 200-500 km. When local phenomena influence the wind resource, the winds do not correlate with sites even some 200 km apart. In Figure 20, the lowest cross-correlations are slightly negative, for Finnish Lapland with Southern Norway sites. For the westernmost site in Southern Norway, the correlation is weak for all other sites, the lowest points in Figure

Table 5. Cross correlation coefficients between wind power productions in the Nordic countries, data for years 2000-2002.

	Norway	Denmark	Sweden	Finland
Norway	1.00			
Denmark	0.33	1.00		
Sweden	0.45	0.71	1.00	
Finland	0.42	0.22	0.45	1.00

20 for distances of 200...800 km come from there. Slightly negative correlations between two points in Europe have been reported from weather data from Ireland/Portugal (1500 km apart) and Spain/Greece (3000 km apart) (Giebel, 2001). The results from correlation between weather station wind speed based data calculated from 9 years in Finland are similar to the ones here for year 2001 (Tammelin&Nurmi, 2001). There is not a significant change in correlation coefficients calculated from different years. A year of hourly data contains enough different weather situations to be able to determine the correlation between the wind power production at different sites.

The cross-correlation can be modelled by exponential fitting, decay parameters (D) of 500…700 have been reported (Giebel, 2001). For this data, D= 500 fits the data (Figure 20).

Looking at large scale wind power production in the countries and regions, the correlations are calculated for 2 years of data (2000-2001) and presented in tables 5-6. For the four countries, Swedish and Danish wind power production is correlated (with the assumption here that most of the Swedish wind power is in the Southern part of Sweden). Wind power production in the other countries is only weakly correlated, with lowest correlation between Denmark and Finland.

Taking a closer look at the regions in the Nordic countries, the largest correlation is again for wind power production in West and East Denmark and South Sweden. These are the areas with least distance apart. Also the two areas in Southern part of Finland are strongly correlated. For other areas, the correlation is not strong. There is weak correlation (0.4...0.5) between the areas in Lapland (the Northern part of Norway, Sweden and Finland), between Southern Norway and Denmark/South Sweden, between South Sweden and the Southern areas of Finland, between the northernmost West coast of Finland and Lapland, Southern and Western parts of Finland, and between Middle and North Norway. There is practically no correlation between Lapland (North Norway, Sweden and Finland) and the Southern areas (Denmark, South Sweden, Norway and to some extent South Finland).

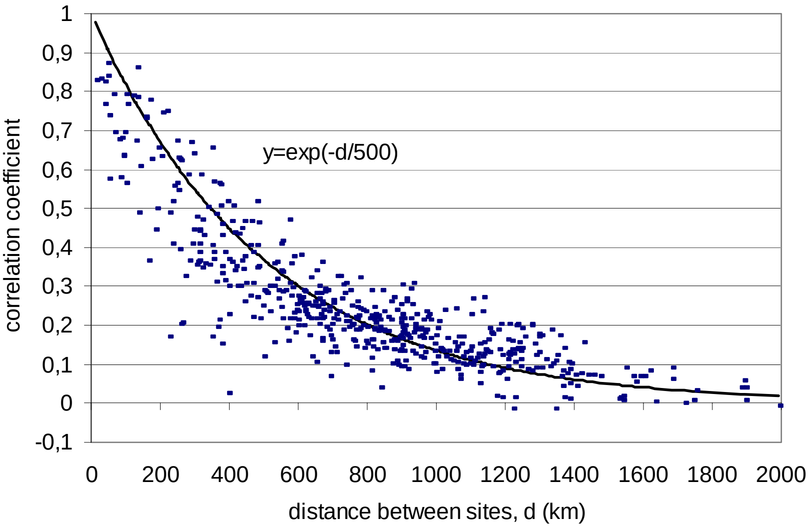


Figure 20. Cross correlation coefficients for the sites in the Nordic data for year 2001.

Table 6. Cross correlation coefficients between the regional wind power production in the Nordic countries, data for years 2000-2002.

	NO South	NO Middle	NO North	DK East Elkraft	DK West Eltra	SE South	SE Middle	SE North	FI South coast	FI West coast South	FI West coast North	FI Lap-land
NO S	1.00											
NO M	0.32	1.00										
NO N	0.17	0.33	1.00									
DK E	0.34	0.12	0.11	1.00								
DK W	0.46	0.18	0.13	**0.86**	1.00							
SE S	0.35	0.18	0.12	**0.82**	**0.77**	1.00						
SE M	0.37	0.28	0.16	0.45	0.47	0.56	1.00					
SE N	0.22	0.34	0.34	0.16	0.18	0.19	0.24	1.00				
FI S	0.26	0.30	0.20	0.27	0.28	0.31	0.52	0.41	1.00			
FI WS	0.28	0.30	0.25	0.22	0.25	0.26	0.42	0.50	**0.71**	1.00		
FI WN	0.18	0.21	0.32	0.10	0.11	0.11	0.18	0.46	0.36	0.56	1.00	
FI Lappi	0.07	0.09	0.37	0.01	0.00	0.00	0.01	0.31	0.13	0.22	0.40	1.00

3.7 Short term variations of wind power production

For power system operation, the variations from day to day, hour to hour and minute to minute are of interest. The larger the area, the longer time scales are affected by smoothing effect. Inside a WF, all the WTs will experience different gusts (seconds), but the hourly wind power production will see approximately the same ups and downs. In a larger area covering several hundreds of km, the weather fronts causing high winds will not pass simultaneously but the good and poor months will occur same time. This can be seen in Figure 21, where the decreasing correlation of the variations is depicted for different time scales (Ernst, 1999). The correlation is here calculated for the differences between consecutive production values (ΔP). For the time series of production values (P), the correlation does not decrease as rapidly as shown here (Figure 20).

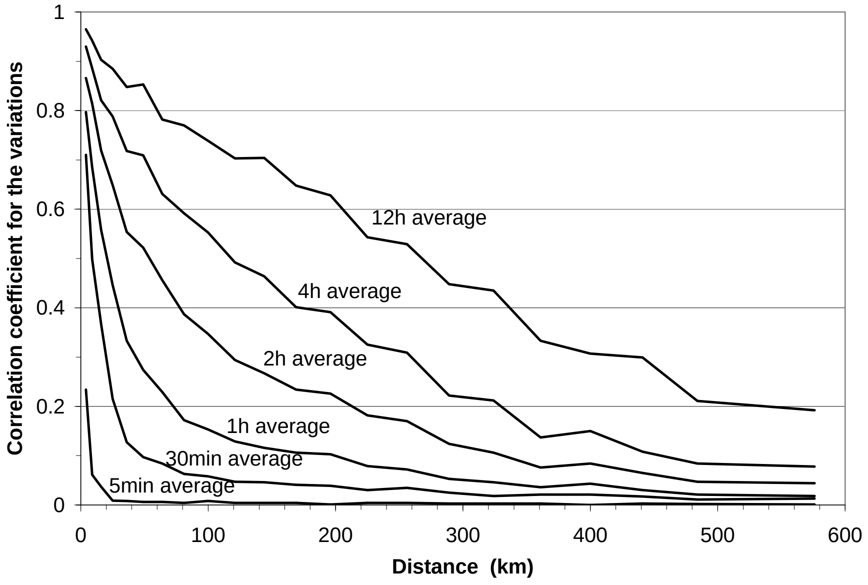


Figure 21. Variations will smooth out faster when the time scale is small. Correlation of variations for different time scales, example from Germany. (Source: B.Ernst,1999)

The in-hour variations

Already the inertia of large rotating blades of a wind turbine will smooth out the very fast gusts of wind. For variable speed wind turbines, the second-to-second variations will be absorbed in the varying speed of the rotor. For a wind farm, the second-to-second variations will smoothed out, as the same gusts will not occur simultaneously at all turbines, situated several hundred meters apart.

The extreme ramp rates recorded from one 103 MW wind farm are 4…7 % of capacity in a second, 10…14 % of capacity in a minute and 50…60 % of capacity in an hour (Parsons et al, 2001). These examples are from a limited area compared with system operation: large wind farm or 3 smaller wind farms some 10 km apart. For a larger area of geographically dispersed WFs, the second and minute variations will not be significant.

For the 15 min variations in Denmark, the production can vary 8.4 % of capacity 6 times per month, and the maximum is 11 % (Nordel, 2000). This is not as much as for the hourly variations, as seen in the following section.

There are means to reduce the fast variations of wind power production. Staggered starts and stops from full power as well as reduced (positive) ramp rates could reduce the most extreme fluctuations, in magnitude and frequency, over short time scales (Kristoffersson et al, 2002). This is at the expense of production losses, so any frequent use of these options should be weighed against other measures (in other production units) in cost effectiveness.

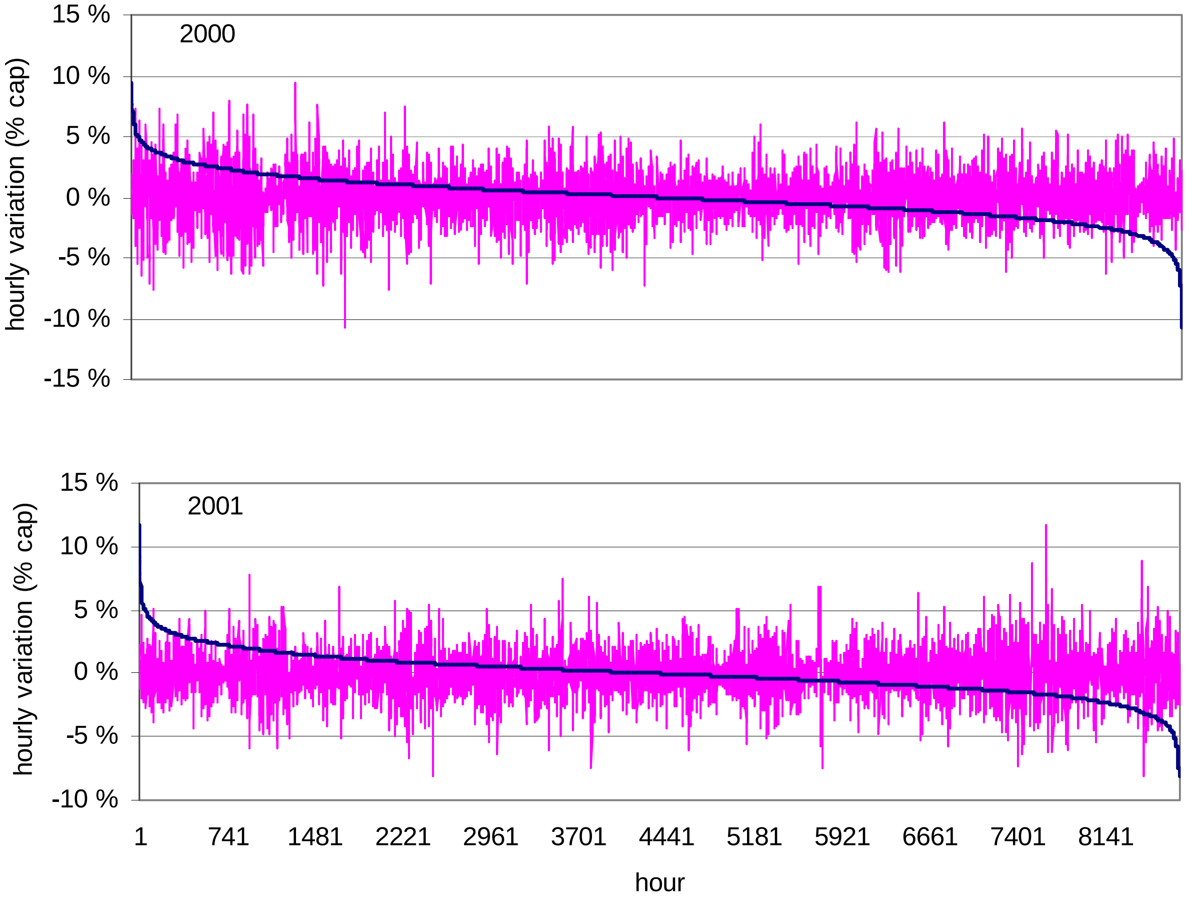


Figure 22. Hourly variations from Nordic wind power production, chronological time series and duration curve, years 2000 and 2001.

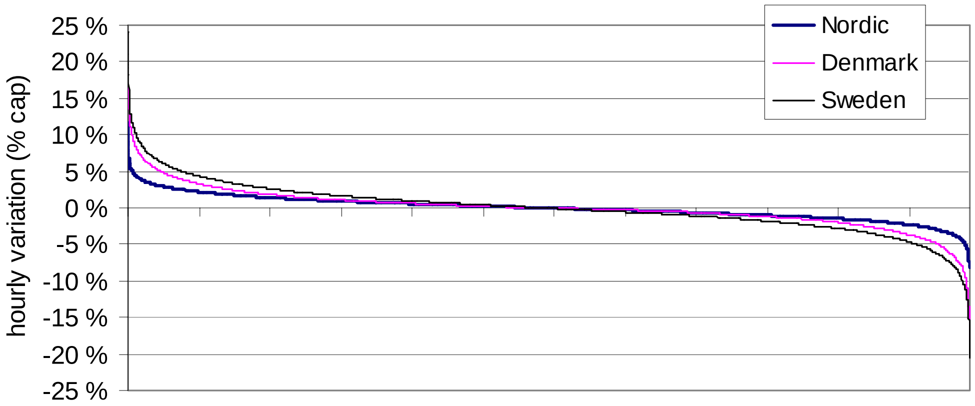
The hourly variations

The hourly variation is here defined as the power difference between two consecutive hours. It is here measured relative to the nominal capacity, to compare it with several countries with different amounts of capacity installed.

$$\Delta P_i = P_i - P_{i-1} \quad ; \quad \Delta p_i = p_i - p_{i-1} \qquad (4)$$

For large scale, dispersed wind power production there will be a significant smoothing effect in the hourly variations. The correlation of the variations between two WTs decreases faster than the correlation of the production. For hourly variations, the correlation becomes weak already in distances less than 100 km (Figure 21, Ernst, 1999). Correlation of hourly variations for the countries and regions were calculated, and most of them were between –0.01 and 0.04, so there is no correlation between the hourly variations. Hourly variations in East and West Denmark are weakly correlated (0.46). For the other closest regions, South Sweden/Denmark, South Norway/West Denmark as well as the Western part of Finland, the correlation of variations is below 0.2.

In Figure 22 and Figure 23 the amount of hourly variations are shown as duration curves. From the hourly time series of wind power production, the hourly variation as the difference between the production at consecutive hours, and these values have been sorted in descending order. In the figure, 0 % means that the power production keeps on the same level and does not vary from one hour to another, positive values indicate situations when wind power production is increasing, and negative values for decreasing production.



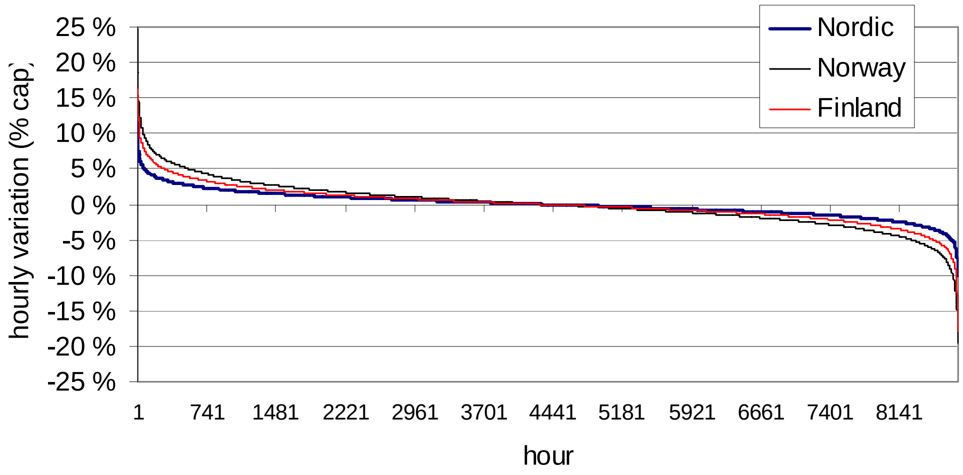


Figure 23. Variation of wind power production from one hour to the next. Duration curve of variations, as % of installed capacity, for the Nordic countries, year 2001.

In Appendix, the hourly variations of wind power production for years 2000–2002 are shown for the 4 countries.

Largest hourly variation is about ± 30 % of capacity when the area is in the order of 200x200 km^2 (like West/East Denmark), ± 20 % of capacity when the area is in the order of 400x400 km^2 (like Germany, Denmark, Finland, Iowa USA) and about ± 10 % in larger area covering several countries, like the four Nordic countries (ISET, 2002; Holttinen, 2002; Milligan & Factor, 2000). For this Nordic data, largest hourly variations are 12 % up and 11 % down. For Norway and Sweden, despite the large area, the variations are higher than for Denmark and Finland. This is due to limited number of sites in the data sets. The Nordic variations are probably overestimated due to this.

These are the extreme values, for most of the time the hourly variations will stay inside ± 5 % of installed capacity (Figure 23 and Table 7). It is notable, that as the average production is about 25 % of capacity, this 5 % of capacity represents 20 % of average power. For the countries, the hourly variations are more than 5 % of capacity 6…20 % of time. For Denmark this is 10 % of time, so probably the large variations of Norway and Sweden data sets are due to too few time series in the countries to represent the variations right. Omitting Norway and Sweden, the conclusion is that the hourly variations of large scale wind power production are about 90 % of time between ± 5 % of capacity and 99 % of time between ± 10 % of capacity. For the total Nordic time series the hourly variations are about 98 % of time between ± 5 % of capacity (Table 7).

Year 2001 had the least variations. Year 2000 had the largest variations for Denmark and Norway. For Sweden and Finland year 2002 has the most variations. But the differences are not very large, except for Norway, which is probably due to better data set for year 2001 (more sites). The largest variation in Denmark was Tuesday evening 8.2.2000 at 21-22 hours up and Sunday afternoon 30.1.2000 at 15-16 hours down. For the Nordic data set largest up-variation was 15.11.2001, and surprisingly during the night, at 01-02

Table 7. Largest hourly variations in the wind power production for Nordic countries, years 2000 and 2001.Maximum variations are as % of installed capacity. The portion of time that the variations are more than 5 or 10 % of capacity is also presented.

		max up-variation	max down-variation	above 5 %	below -5 %	above 10 %	below -10 %
Denmark	2000	20.1 %	-23.1 %	4.9 %	4.9 %	0.6 %	0.5 %
Denmark	2001	16.7 %	-18.0 %	4.0 %	3.7 %	0.5 %	0.4 %
Denmark	2002	16.2 %	-19.5 %	4.5 %	4.6 %	0.8 %	0.6 %
Finland	2000	14.7 %	-15.6 %	3.0 %	3.2 %	0.2 %	0.2 %
Finland	2001	16.2 %	-14.9 %	3.2 %	3.0 %	0.2 %	0.1 %
Finland	2002	15.5 %	-15.7 %	3.7 %	3.3 %	0.3 %	0.3 %
Norway	2000	26.9 %	-21.2 %	10.1 %	10.5 %	1.9 %	1.7 %
Norway	2001	24.8 %	-19.6 %	6.2 %	5.7 %	0.7 %	0.6 %
Norway	2002	27.4 %	-29.3 %	9.8 %	9.6 %	2.0 %	1.6 %
Sweden	2000	21.6 %	-20.3 %	6.3 %	6.3 %	0.8 %	0.7 %
Sweden	2001	24.1 %	-20.5 %	6.4 %	6.3 %	1.0 %	0.8 %
Sweden	2002	19.9 %	-26.9 %	7.4 %	6.8 %	1.1 %	1.0 %
Nordic, evenly	2000	9.5 %	-10.7 %	0.6 %	0.7 %	0.0 %	0.0 %
Nordic, evenly	2001	11.7 %	-8.1 %	0.6 %	0.5 %	0.0 %	0.0 %
Nordic, evenly	2002	8.7 %	-9.0 %	1.0 %	0.7 %	0.0 %	0.0 %
Nordic 2010	2000	13.1 %	-14.5 %	1.8 %	1.8 %	0.0 %	0.0 %
Nordic 2010	2001	9.6 %	-12.2 %	1.4 %	1.3 %	0.0 %	0.0 %
Nordic 2010	2002	10.2 %	-12.5 %	1.8 %	1.4 %	0.0 %	0.0 %

hours. This was due to wind power increasing in Finland (by 16 % of capacity), Norway (by 25 % of capacity) and Denmark (by 8 % of capacity). The largest down-variation was Wednesday 15.3.2001, at 16-17 hours, when there was a large variation (17 % of capacity) in Denmark simultaneously with nearly 20 % variation in Norway and nearly 10 % variation in Sweden. The initial production level was less than 40 % of capacity in all the countries, so cut-off wind speed was not the explanation.

Probability of significant variations is a function of production level. Significant changes occur most probably when wind farms are operating between 25...75 % of capacity, as this is the steep part of the power curve when changes in wind speed produce largest changes in power output of the turbines. For large scale wind power, the production is rarely above 75 %, so an analysis to Nordic data was done for the production level of above 20 % of capacity (at the first hour). Hourly variations were analysed for these periods only. Example from duration curve of variations is shown in Figure 25. It can be seen, when comparing for all the hourly variations in Figure 23, that the large variations occur nearly twice as often for the countries when looking this way (Table 8).

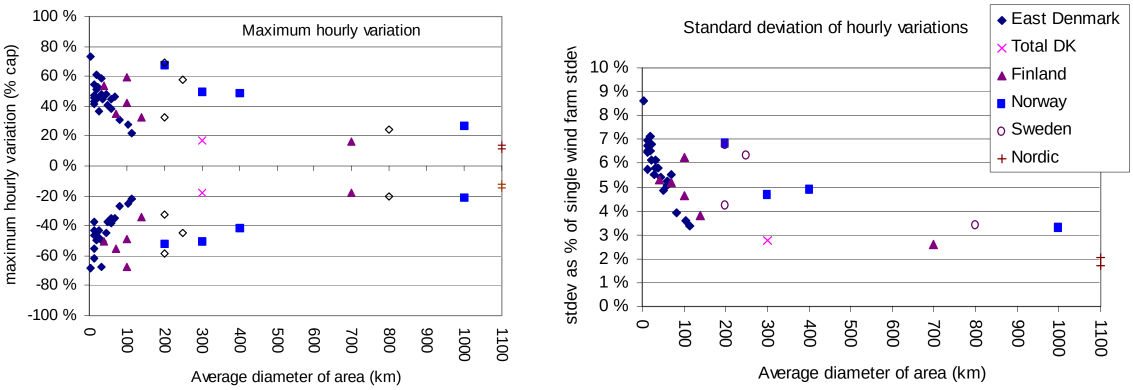


Figure 24. Maximum hourly variation in wind power production for the data for Nordic countries.

Reductions in standard deviation for hourly time series is a measure of reduced variability in the time series with geographic dispersion of wind power. The standard deviation of hourly time series will reduce to 70–80 % of the single site value (Figure 7 and Focken et al, 2001). For the Nordic area, the reduction is to about half of the one site value ($\sigma = 14.5$ %).

The standard deviation of the time series of fluctuations ΔP will decrease even faster, from about 10 % for a single turbine to less than a third (3 %) for an area like West Denmark (Milborrow, 2001). For Nordic data, the reduction in maximum variations and standard deviation of variations is presented in Fig.28. The Norway and Sweden data give again larger standard deviation values than Denmark and Sweden, due to lack of real large scale wind power data.

As can be seen from Figure 24, the smoothing effect is more pronounced with more turbines and more separation. The smoothing effect of a specified area has a limit, that is, the time series will not get smoother if more and more turbines are added from the same area. For Germany, for example, it has been estimated that 30 sites will be enough to get the low variations (Focken et al, 2001). After saturation, the only way to increase the smoothing will be to increase the area – which has a limit somewhere, too. In Figure 24 it is also obvious that increasing the area from that of Denmark, the decrease in the statistical parameters shown here is slower.

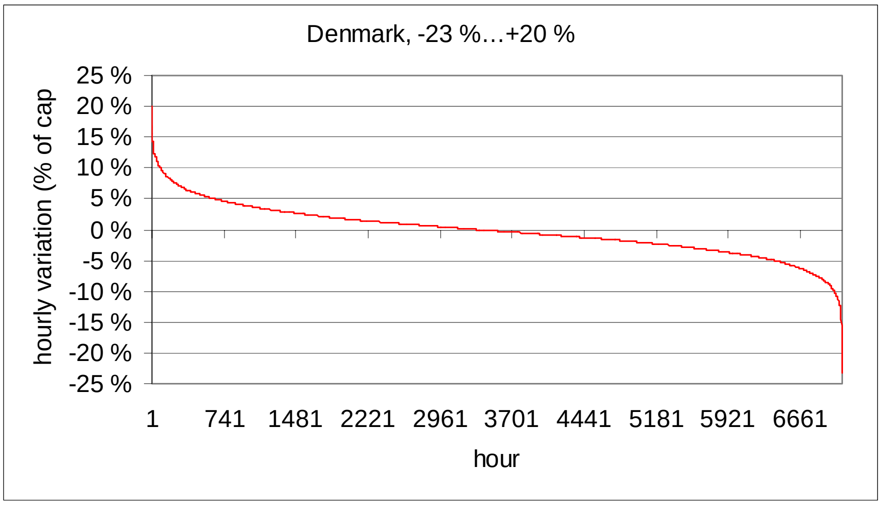


Figure 25. Duration curve of hourly variations, when the initial production level has been above 20 % of capacity. Data from years 2000 and 2001. (The x scale is not the same as in Fig.26, as the total amount of hours with this production level is not as much as the total number of hours in 2001.)

Table 8. Largest hourly variations in the wind power production for Nordic countries, when taking only the periods with production more than 20 % of capacity (years 2000 and 2001).

	Nordic	Denmark	Finland	Norway
time above 20 %	56.09 %	40.40 %	47.64 %	66.81 %
max up-variation	11.4 %	20.1 %	16.2 %	26.9 %
max down-variation	-12.2 %	-23.1 %	-15.5 %	-21.2 %
time above 5 %	1.5 %	9.0 %	5.1 %	10.1 %
time below - 5 %	1.6 %	9.7 %	6.0 %	11.3 %
time above 10 %	0.0 %	1.2 %	0.4 %	1.7 %
time below - 10 %	0.0 %	1.2 %	0.3 %	1.7 %

Table 9. Maximum variations from the Nordic wind power production (hourly values from years 2000 – 2002).

	Nordic	Denmark	Finland	Norway	Sweden
4 hour variations: max down	-27.5 %	-61.9 %	-36.6 %	-54.6 %	-48.6 %
4 hour variations: max up	32.7 %	52.9 %	51.6 %	55.2 %	47.6 %
12 hour variations: max down	-43.9 %	-73.6 %	-66.6 %	-84.8 %	-66.4 %
12 hour variations: max up	51.1 %	79.1 %	72.8 %	74.2 %	73.9 %

Diurnal variations in output can help indicate when significant changes in output are most likely to occur (Poore & Randall, 2001). The average hourly variations of wind power production are zero – there are as much up and down variations. However, when plotting the average hourly variation as of time of day, the average is no longer zero for all hours of the day. There are more upward changes during the morning hours and more downward changes during the afternoon hours, as can be seen in Figure 26. This is more pronounced during summer, as is the diurnal variation of the production. Also the

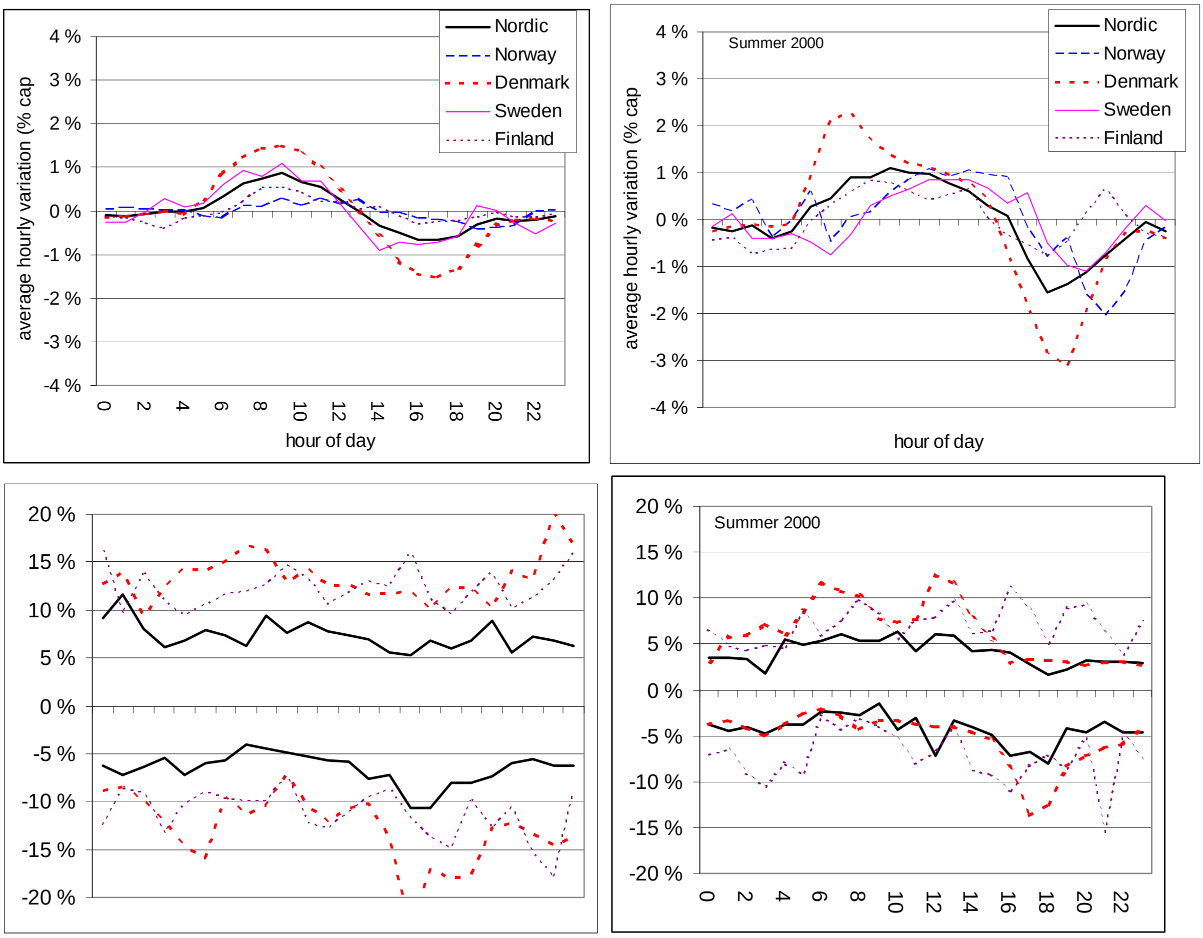


Figure 26. Diurnal dependence of variations. All data and summer 2000. Above: average hourly variations, as of time of day. Below: maximum variations, up (positive) and down (negative).

maximum variations in the data set occur in morning hours for the upward changes and in the evening hours for the downward changes. The maximum variations are less in summer.

Variations for longer time scales

For longer time scales, 4…12 h variations, short term prediction tools for wind power give valuable information on the foreseeable production levels, and expected variations of wind power production.

From the Nordic data set, the maximum 4- and 12-hour-variations are presented in Table 9. The range of 4 hour variations is about ± 50 % of capacity for one country. This has also been reported for a longer following period from Germany (ISET, 2002). For the Nordic area it is well inside ± 35 % of capacity according to this 3-year data set.

The maximum 12-hour variation for the Nordic area is ± 50 % of capacity. Taking larger areas, like the Northern Europe, and more years of data, ± 30 % change in production 12 hours ahead occurs about once a year (Giebel, 2000).

3.8 Predictability of wind power production

Wind power prediction plays an important part in the system integration of large scale wind power. When the share of installed wind power is significant, the knowledge of the on-line production and predictions 1…36 hours ahead are needed. Day-ahead predictions help the scheduling of conventional units: planning the start-ups and shut-downs of slow starting units in an optimised way, keeping the units running at best possible efficiency, saves fuel and thus operational costs of the power plants. Predictions 1-2 hours ahead help keeping up the optimal amount of regulating capacity at the system operators' use (Milligan et al, 1995). In wind power production forecasts, as is the case for load forecasts, too, the errors decrease when forecasting for a larger area (Holttinen et al, 2002).

Predictability is most important at times of high wind power production, and up to 6 hours ahead, giving enough time to react on varying production also by start-ups and shut-downs of most of the thermal power plants. An estimate of the uncertainty, especially the worst case error is also relevant information.

Forecast tools for wind power production are still under development and improvements are expected (Giebel et al, 2003). The predictions of the power production 12 hours-ahead or more rely almost entirely on meteorological forecasts for local wind speeds. In northern European latitudes, the variations of wind power production occur due to meteorological weather systems passing the area, causing high winds, which calm down again. The largest error component comes from the wind speed forecast of the Numerical Weather Prediction models. So far the accuracy of ± 2-3 m/s, ± 3-4 hours has been enough for wind speeds in weather forecasts, but electricity market (and system) requires more precise knowledge of wind power production.

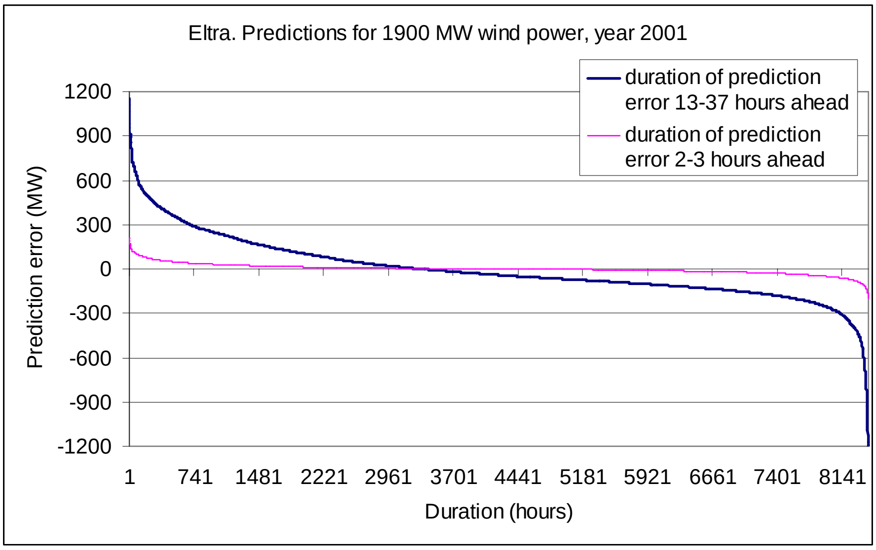


Figure 27. Prediction errors for wind power production (state-of-the-art year 1997 for the prediction tool in use).

An example of the forecast errors is presented in Figure 27 for West Denmark, where the system operator Eltra is responsible for most of the wind power installed in the area. The wind power prediction tool in use in year 2001 was dated from year 1997. For Nordpool electricity market (prediction horizon 13...37 hours ahead) the mean absolute error is 8-9 % of installed capacity. However, for market operation this results in 38 % of yearly production mispredicted. For comparison, load is predicted with 1.5…3 % error (mean absolute error, as % of peak load), which results in about 5 % of yearly energy mispredicted. For prediction 2 hours ahead the prediction tools for wind power work significantly better (Figure 27; Holttinen et al, 2002).

For larger areas the prediction errors decrease. For East and West Denmark, for example, the errors for day-ahead predictions are to the opposite sides for about a third of time (Holttinen et al, 2002). For the distance in the direction of most weather systems passing, West-East, adding East Denmark brings 100 km, or 50 % more to West Denmark.

3.9 Representative data for large scale wind power production

To study the impacts of large scale wind power production, the data should be representative – both in time and space. Depending on what impact we are looking at, we should take an average year production, or a low or high wind year, to see the extreme situations for system planning purposes. This means taking production from a representative time period to study. Depending on what impact we are studying, the wind power production time series should be representative for the area in question. For example, large scale wind power impacts on the power system operation, should take the production from large area, with proper smoothing effect present in the data. This means taking production from representative space.

Checking out the representativeness of time period studied is quite straightforward, when long term wind power data exists. For checking up the representativeness in geographical smoothing, no examples were found in the references. Below some basic parameters are picked up to form a guideline in this respect.

Representativeness of the study years

Here we look at the years in question: 2000-2002. Wind power production indices from national wind power production statistics are presented in Figure 28 (Laakso, 2003; Carlstedt, 2003; Naturlig Energi, 2003). Wind power production index is a measure of one year's production compared with the long term average production. 100 % means that the yearly production was like the long term average. In Fig. 31 it can be seen that the yearly production varies between 80...120 %. In Finland, the coastal areas South and West experience a somewhat different wind resource variations, this is why the production indices are calculated for 4 sites (Laakso, 2003). The production indices for Finland are here calculated as weighted average of these indices, using the large scale wind power capacity distribution assumed in this study (Table 1). For Norway this analysis was not done due to lack of long term data. However, the Norwegian wind power production seems to experience the same trends as for the other Nordic countries (Table 2), even if not as strongly.

Year 2000 was close to average (95 % in Denmark, 97 % in Finland, 102 % in Sweden), and year 2001 was clearly less windy than average (80 % in Denmark, 87 % in Finland, 88 % in Sweden). Year 2002 was close to average in Denmark and Sweden (95 % in Denmark and 98 % in Sweden), and a very low wind year for Finland (76 %).

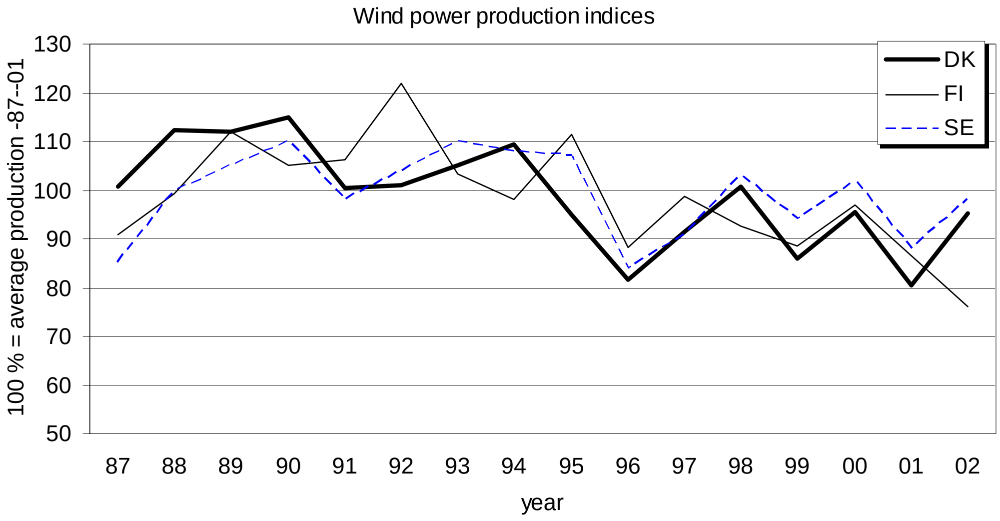


Figure 28. Yearly wind resource in 1987...2002, according to production statistics of wind energy in Nordic countries (DK=Denmark, FI=Finland, SE=Sweden).

The production index can be used in determining the long term average wind power production from only one year of realised production data, by dividing the year's production with the year's index value. For the countries presented here in Figure 28, using the average production in 2000-02 compared with the average production index 2000-02, we get roughly 24-26 % of capacity as the long term average wind power production.

As a total period, 2000-2002 will give a production that is less than average: 90 % of the average production in Denmark, 87 % in Finland and 96 % in Sweden. However, as the data contains also high wind months, for example the first part of year 2000 (Figure 13; monthly production indices in Carlstedt, 2003 and Naturlig Energi, 2003) there are also representative periods of high wind situations in the data.

Representativeness of the geographical spreading of data

Based on the detailed statistical analyses, it can be estimated, how well the data represents large scale wind power production. The data used for wind power fluctuations is critical in the studies for wind power impacts on power system operation. Not to upscale the fluctuations when upscaling installed wind power in the system, the statistical characteristics for large-scale production should be looked for in any simulated or meteorological data based wind power time series (Milborrow, 2001).

As Denmark data is real large scale wind power data of thousands of wind turbines, the comparisons made can be used as a basis to estimate how well the data sets constructed for Norway and Sweden and Finland represent large scale wind power production.

Finland and Norway are considerably larger areas than Denmark, so also the smoothing effect should be stronger there. For Sweden, there is the possibility of concentrating most of the wind power capacity south of Stockholm, which means that Sweden should get closer to the same smoothing effect than in Denmark – probably more if at least some of the capacity was installed to the Northern part of Sweden.

Summing up the statistical properties for an hourly time series of large scale wind power production, the following were found:

- Standard deviation of the hourly production series should be 20–22 % of capacity for an area like Denmark (300 x 200 km^2), if larger area, then less than 20 % (Finland 18 %, Norway 20 %, Sweden 18 %, Nordic 15 %).
- Maximum hourly production should be less than 100 %: 85...95 % depending on how large the area in question is (Denmark 93 %, Finland 91 %, Norway 93 %, Sweden 95 %, Nordic 87 %).
- Duration of calms should be non existent or limited (production below 1 % of capacity 5 % of time in DK, 1–2 % of time in FI and SE, <1% in NO; minimum production in Nordic data set 1.2 % of capacity).
- Standard deviation of the hourly variation series should be less than 3 % of capacity (Denmark 2.9 %, Finland 2.6 %, Norway 3.9 %, Sweden 3.5 % and Nordic 1.7 %).
- The hourly variations should be in between ± 20 % of capacity, or even less if the area is larger than the size of Denmark (Denmark -23…20 %, Finland -18…16 %, Norway -21…27 %, Sweden -20…22 % and Nordic -11…12 %).

The smoothing effect is presented graphically in Figure 7 and Figure 24 where the trends in the statistical parameters are depicted as a function of the size of the area. Finnish data set is in line with Denmark data set for reduction of standard deviation, maximum hourly variations and the standard deviation of variations. Norwegian and Swedish data sets have the statistical properties above those of Denmark. When looking at the basic statistics for the production time series, there is not a clear signal that the Norwegian and Swedish data would be unrepresentative, as taking even few time series from the countries from different locations of the area gives a basic smoothing effect in the range of production. The analysis on variability, especially the standard deviation of hourly variations, reveals the caveats of the Swedish and Norwegian data sets.

The conclusion is that the Finnish data set can be upscaled to represent large scale wind power production, whereas the Norwegian and Swedish data sets will exaggerate the hourly variations if upscaled. Combining the 4 data sets to form a Nordic data set probably overestimates the variations somewhat, but a continuing smoothing effect can be seen (Figure 7 and Figure 24). It has thus been considered representative for the study of large scale wind power.

There will probably be a slight overestimation of variability for Finnish data when upscaling the data to large scale wind power production. Even for Denmark, there can be some caveats as to how well the data represents future wind power production. In the future, there will be less turbines and sites, but better production from MW scale high turbines, especially for offshore. When a substantial share of wind energy comes from large offshore wind farms, this will have an impact on the production, bringing about a less dispersed and thus more variable production, but also higher duration, as there are less calms than on shore (Pryor & Barthelmie, 2001).

4 Wind models

The WILMAR Planning Model needs two types of wind power time series data as input:

- The estimated wind power production by region on hourly basis for one full year, $P_w(R,h)$, and
- a simulated estimate of the short-term prediction of the wind power production by region, $P_{wp}(R,h,T)$,

where

R	indicates the WILMAR defined Region
h	indicates the hour number of the full year (0..8759)
T	indicate the forecast length (1..48 hours).

The two time series, P_w and P_{wp}, are generated based on real, historical wind speed and/or wind power time series made available for the project. The real wind *speed* time series represents the wind at specific sites. The real wind *power* time series of the aggregated power production for a given area represents to some extent the wind resources within the area. While wind *speed* data are most convenient for the modelling, the aggregated wind *power* data available may better represent the entire specific region.

Two models developed as part of WP 2 in the WILMAR project generate the two wind power time series required as input to the WILMAR Planning Model:

- the WILMAR Wind Power Model (WILMARwind) and
- the WILMAR Short Term Wind Power Prediction Scenario Simulation Model (WILMARwindpredict).

In addition an intermediate model needed for the wind power prediction model estimates

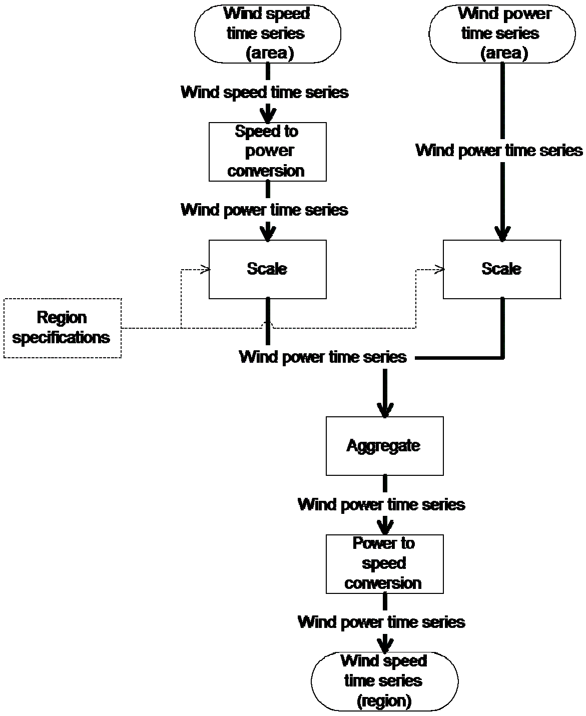


Figure 29: Overview of the generation of the wind power time series needed for the WILMAR Planning Model.

/ extracts a representative wind speed time series for an area based on an aggregated wind power time series for the area

- the WILMAR Power-to-Wind Model (WILMARpower2wind).

Three WILMAR WP2 sub-models are described below:

- the WILMAR Wind Power Model
- the WILMAR Power-to-Wind Model and
- the WILMAR Short-Term Wind Power Prediction Simulation Model.

The WILMAR Wind Power Model

The WILMAR Wind Power Model generates the wind power time series on hourly basis for each WILMAR Region to be used as input for the WILMAR Planning Model. The Wind Power Model includes a model to estimate the aggregated power production based on one or more wind speed time series for the area.

Inputs to the Wind Power Model are

- Normalised wind speed raw data time series on hourly basis
- Normalised wind power raw data time series on hourly basis
- A set of parameters – including a specification of the anticipated installed wind power capacities area by area.

In version 1 of the Wind Power Model the estimation of the wind power production for each Region is based on one wind speed time series only.

The WILMAR Power-to-Wind Model

The WILMAR Power-to-Wind Model estimates a representative wind speed time series based on an aggregated wind power time series. This is mainly needed as input for the WP Prediction Simulation tool, operating on wind speeds instead of wind power.

In version 1 the conversion from wind power time series to wind speed time series is based on the ‘aggregated power curve’ as described below. The double-determination of the wind speed (if the wind speed is low or high) is solved by comparisons with neighbouring wind speed information.

The WILMAR Short-Term Wind Power Prediction Simulation Model

The WILMAR Short-Term Wind Power Prediction Simulation Model simulates for each hour during the year a set of realistic wind power prediction scenarios on hourly basis and 1-3 days ahead to be used as input for the WILMAR Planning Model.

The simulated uncertainty of the wind power prediction is user defined.

The simulated wind power prediction scenarios will best possible represent the various wind correlations – including:

- the autocorrelation of the prediction errors over the forecast length for a specific site
- the correlations of the prediction errors between predictions produced at different times for a specific site
- the correlations of the predictions between neighbouring sites
- the ‘phase’ errors.

In version 1 scenarios are generated by KTH’s two-step ARMA model: first one scenario is generated and treated as a simulation of the expected forecast; next a huge number of

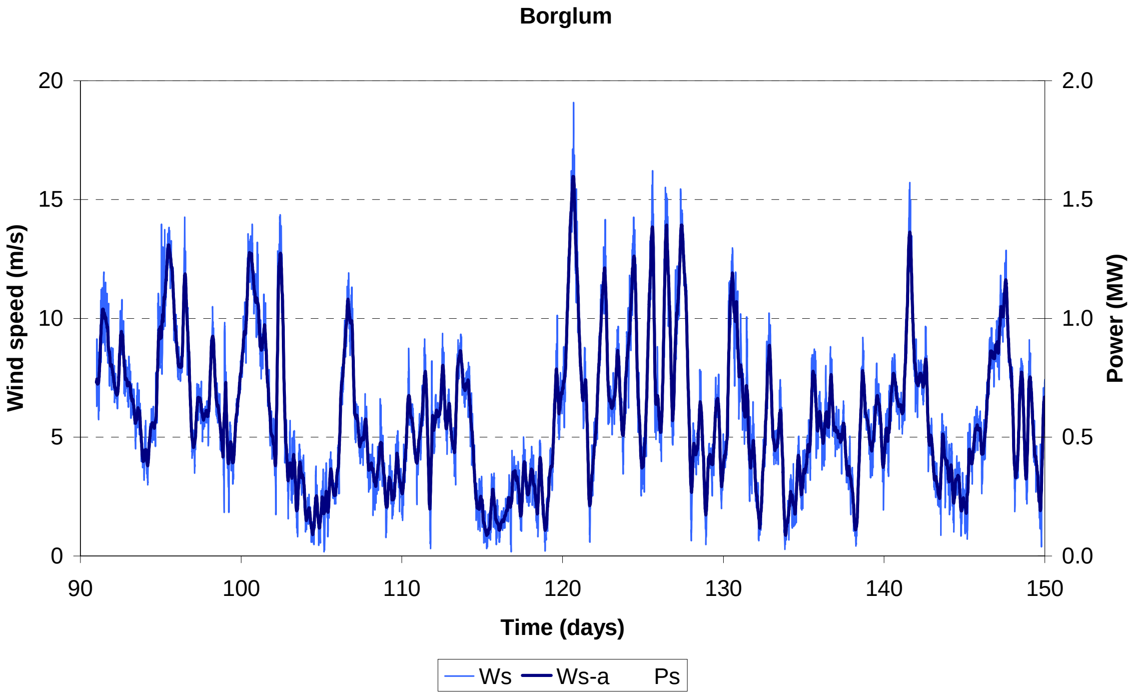


Figure 30: Sample of original ('Ws') and smoothed ('Ws-a') wind speed time series.

scenarios are generated on basis of the first scenario representing the uncertainty in the forecast.

In version 1 the scenario are generated on-line while running the planning model. None of the scenarios generated as input for the planning model will be saved. The planning model reduces the number of scenarios to few scenarios and these scenarios will be saved for detailed inspection.

Version 1 also does not deal explicitly with the phase error. This type of error happens when the Numerical Weather Prediction (NWP) that normally is the source for the wind power predictions, does predict a coming change in wind speed correctly, but for the wrong time. Often, this phase shift is in the range of 4-6 hours (at least in Denmark).

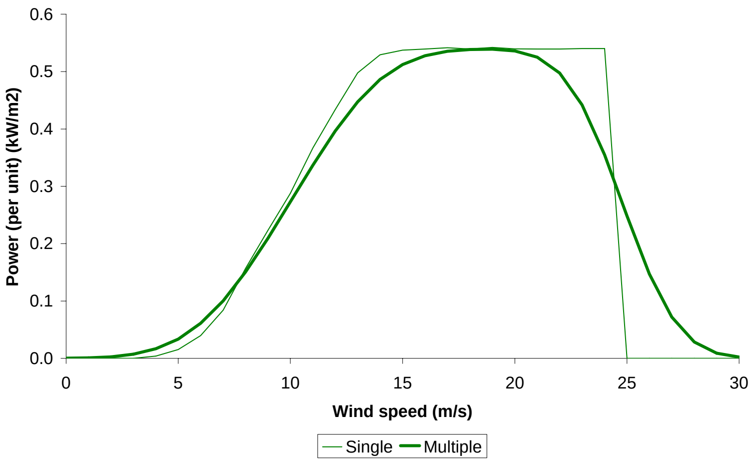


Figure 31: A standard normalised power curve ('Single') and the corresponding smoothed power curve ('Multiple').

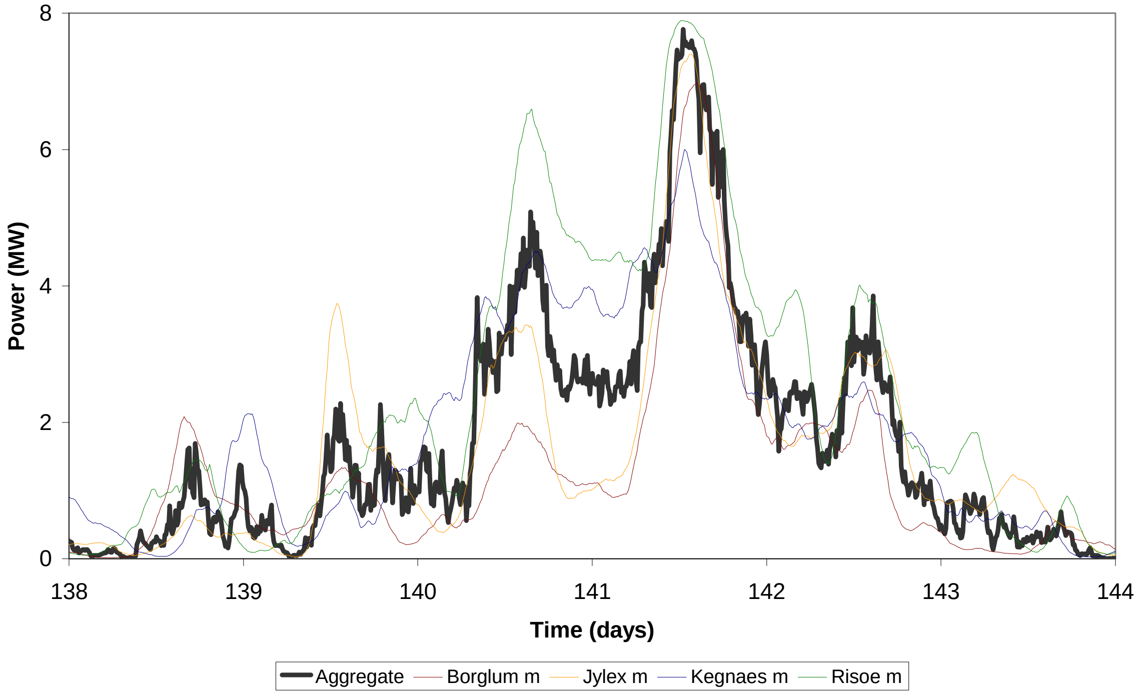


Figure 32: Actual and simulated aggregated power output for 4 wind turbines distributed over several hundreds of kilometres.

4.2 Wind power model

A simplified multi-turbine power curve approach has been developed to simulate the smoothing effects of the aggregated power output from a number of wind turbines within an area. The methodology is used to derive a qualified estimate of a time series of the aggregated power generation from a number of (similar) wind turbine units within the area, based on only one wind speed time series, representative for the area, and a wind turbine power curve representative for the wind turbines in question. The extension of the area may vary from few kilometres (for a wind park) to several hundred of kilometres (for a region).

For this purpose an artificial, empiric based 'multi-turbine power curve' representative for the aggregated power generation has been developed. The methodology take into account the smoothing effects in both time and space.

The methodology has been verified by real data and compared to using a standard power curve and no smoothing of time series data.

The inputs needed are:

1) a wind speed time series representative for the area and

2) a standard wind turbine power curve representative for the wind turbines to be covered.

The methodology is described in a step-by-step guide including:

1. The wind is characterised in terms of the wind speed distribution, the mean wind speed and the turbulence intensity.
2. The wind speed time series is adjusted to relevant hub height and smoothed by a moving block averaging using a time slot representing the travelling time over the area.

3. The ‘smoothed power curve’ is found based on a representative standard power curve and the standard deviation of the spatial wind speed distribution, and scaled appropriate to represent the total installed wind power capacity.
4. The aggregated wind power time series is finally derived by applying the smoothed and scaled power curve on the smoothed and adjusted wind speed time series.

4.3 Wind power prediction simulation model

Available data:

The model is based on that we have the following data available:

Wind speed series: It is assumed that there are i=1…N areas, and in each area there are j=1…n(i) wind speed series. Each wind speed series consists of k=1…K measured wind speeds, v(i,j,k), e.g., consecutive hourly mean values. This implies that each series (series j in area i) can be written as

v(i,j,1), v(i,j,2), v(i,j,3), … v(i,j,K)

Wind speed forecast errors: It is assumed that data concerning the accuracy of wind speed forecasts in different areas are known. In reality the forecast uncertainty is different in different situations, and generally this is not a problem to consider. The question is though how much information is available concerning this issue. The modeling is based on that the wind speed forecast errors are available according to Figure 33.

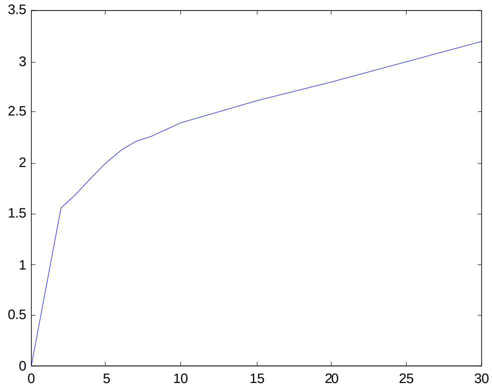


Figure 33: Wind speed forecast errors from Törnevik et al, Forecast of wind in the layer between 50 and 150 meters, SMHI, 1985

Probably there are better methods available today but about the same accuracy is presented in Landberg, *Short-term Prediction of Local Wind Conditions*, PhD thesis, Risø 1993. It can be assumed that also with better forecasts the structure of the forecast errors is probably about the same with a fast increase of forecast errors up to some few hours and then a much slower increase. This behaviour is still common for most modern prediction models, although the accuracy has increased somewhat due to the improvements in the underlying NWP models. See also Giebel et al, 2003.

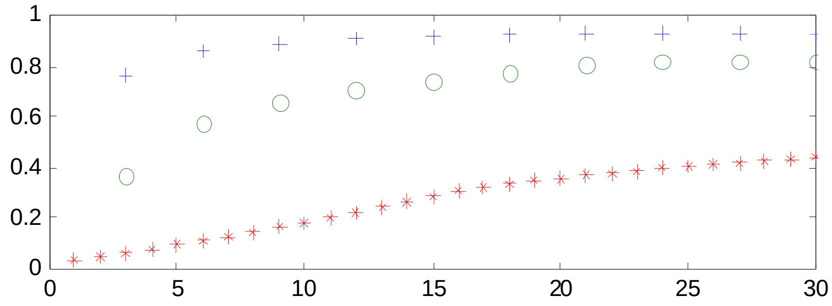


Figure 34: Correlation between forecast errors for different pairs of stations.

Wind speed forecast error correlation

When wind speeds are forecasted for the same time period, but for different locations, then the forecast errors will be correlated. The reason is that unpredicted wind conditions will affect both sites. In general one can say that if two wind sites are far from each other, then the short time forecast errors will be less correlated, since the unpredictable wind situations are not the same for the two sites. For longer forecasts the unpredictable wind conditions are though similar for the two sites, so the forecast errors become more correlated.

In Figure 34 three examples of correlation between forecast errors are shown. The distance between the stations are Maglarp-Bösarp (15 km), Maglarp-Sturup (26 km), Näsudden-Ringhals (370 km). No real wind speed forecasts have been available in any of these sites, but instead it has been assumed that *persistence forecasts* have been used, and the figure shows the correlation between forecast errors when persistence forecasts are applied for different forecast lengths.

In the figure it is clear that the closer the stations, the higher the correlation between forecast errors. It is also shown that the correlation increases with forecast lengths. It can be noted that if the forecasts are improved compared to the here assumed method (all new methods are better than persistence forecast), then probably the correlation will decrease compared to Figure 34. The motive is that better forecasts means that weather changes that affect the region will be better forecasted, and the forecast errors will then probably more depend on local (uncorrelated) unpredictable changes. In the examples below the curve in the middle, Maglarp-Sturup, is used for model parameter identification.

Very little literature exists on the cross-correlations between errors in modern NWP-based predictions. Focken et.al. (2002) show the cross-correlation to rise with increasing horizon and drop with increasing distance. However, this is only for predictions based on a single NWP model. It has to be assumed that predictions based in different countries would use different NWP models, which probably would decrease the error correlation below the level that would be expected in a single NWP. However, to date no data exists on this.

Model for one site

In the proposed model we can assume that the measured wind speeds instead can be viewed as available forecasts. The aim is then to simulate realistic possible outcomes, which have the correct statistical behavior concerning forecast errors and correlation between different forecasts.

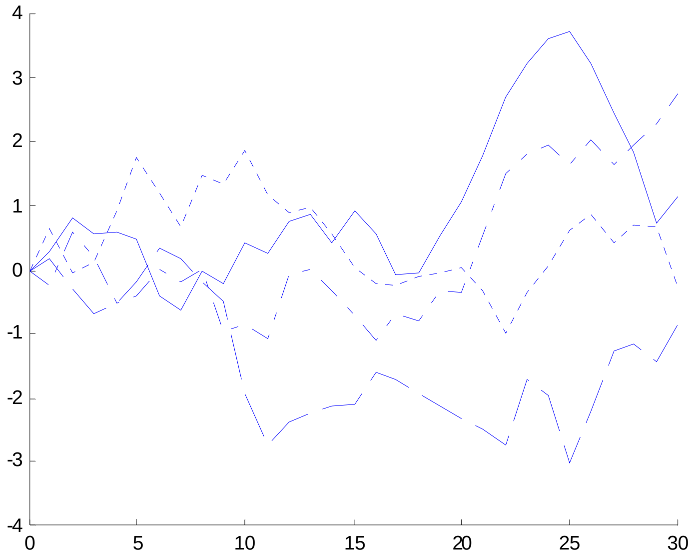


Figure 35: Four examples of ARMA(1,1)-outcomes of wind speed forecast errors.

Below we propose how these realistic possible outcomes can be simulated. The first step is to show how wind speeds at one site can be simulated. The method will use a ARMA(1,1) approach, i.e., Auto Regressive Moving Average series. This series is defined as

$$\begin{aligned} &X(0) = 0 \\ &Z(0) = 0 \\ &X(k) = \alpha X(k-1) + Z(k) + \beta Z(k-1) \end{aligned} \qquad (1)$$

where

X(k) = wind speed forecast error in k-hour forecast

Z(k) = random Gaussian variable with standard deviation σ_Z

This approach means that wind speed forecast errors are simulated. The real wind speed for each hour can then be calculated as the sum of the wind speed forecast (=measured wind speed) and the wind speed forecast.

Now assume that α=0.95, β=0.02 and σ_Z=0.5. Figure 35 then shows 4 examples of possible outcome for the ARMA simulation of forecast errors.

The variance for the ARMA(1,1) model, i.e. variance of X(k), can be calculated in the following way.

$$\begin{aligned} &V(0) = 0 \\ &V(1) = \sigma_Z^2 \\ &V(k) = \alpha^2 V(k-1) + (1 + \beta^2 + 2\alpha\beta)\sigma_Z^2 \end{aligned} \qquad (2)$$

For $k \geq 2$, this equation can be rewritten as

$$V(k) = \sigma_Z^2 \left(\alpha^{2(k-1)} + (1 + \beta^2 + 2\alpha\beta) \sum_{i=1}^{k.1} \alpha^{(i-1)} \right) \qquad (3)$$

The standard deviation of the forecast error is then calculated as

$$\sigma\big(X(k)\big) = \sqrt{V(k)} \qquad (4)$$

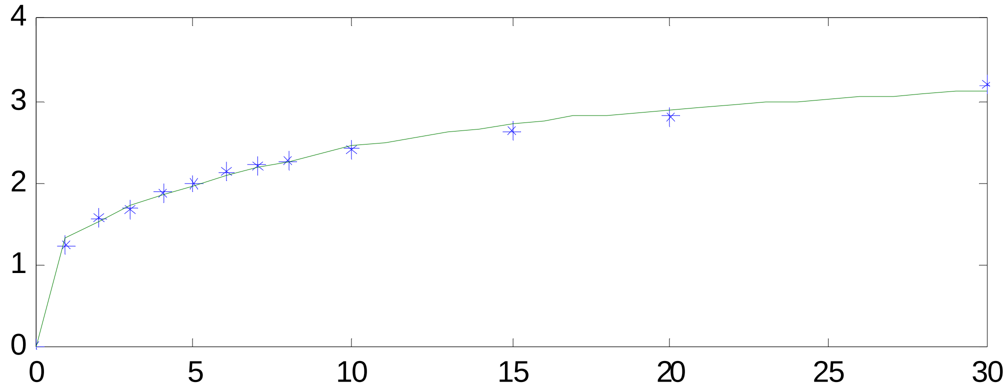


*Figure 37: RMSE for forecast errors, * = from Figure 36, straight line for ARMA-series with estimated parameters α=0.97, β=-0.38 and* σ_Z*=1.31.*

In Figure 36, the standard deviation for the ARMA(1,1) series with the above parameters are shown together with the standard deviation of 50 different outcomes.

The next step is now to identify the parameters α, β and σZ. The method applied here is to identify them in such a way that the forecast error (according to Figure 36), will be as close as possible to available data (as in Figure 33). Mathematically this can be formulated as

$$\min Q(\alpha,\beta,\sigma_Z) \qquad (5)$$

where

$$Q(\alpha,\beta,\sigma_Z)=\sum_{i=1}^{m}\left[RMSE_{measured}(t)-RMSE_{ARMA}(t)\right]^2 \qquad (6)$$

and

$RMSE_{measured}(t)$ = measured RMSE data according to Figure 33 for t-hour forecast

$RMSE_{ARMA}(t)$ = calculated ARMA RMSE data according to Figure 36 for t-hour forecast

M = number of forcast errors used in the optimization

This is a so-called *unconstrained nonlinear optimization problem* and can be solved with e.g. the Nelder-Meade simplex algorithm (= routine fmins in MATLAB). In Figure 37 this method is applied to the data in Figure 36.

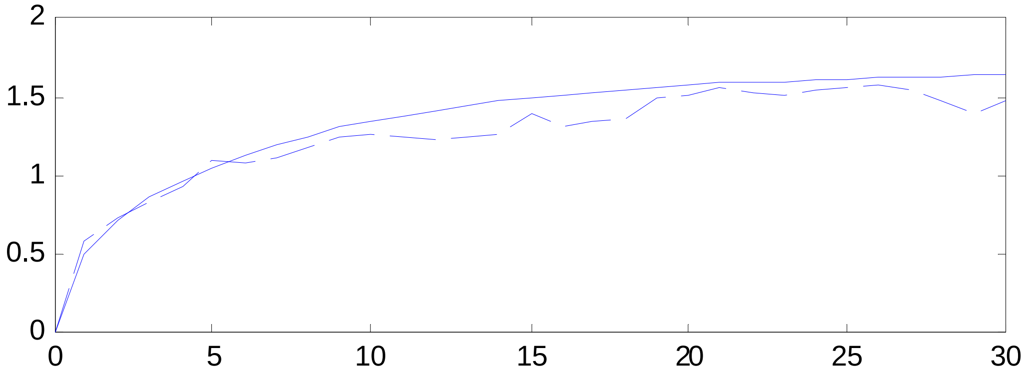


Figure 36: Forecast error standard deviation analytical (straight line), 50 series (dashed line).

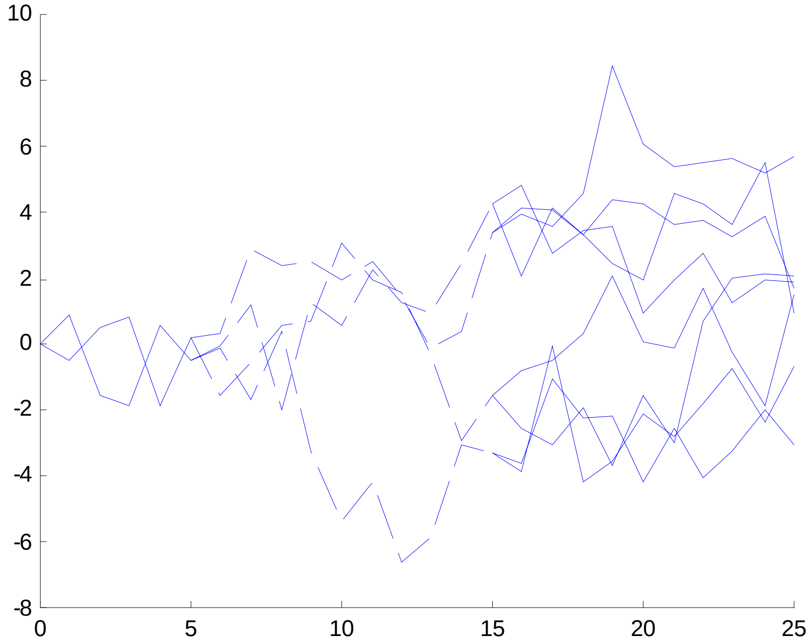


Figure 38: A forecast error tree with parameters according to Figure 37. Two alternatives in hour 0, 5 and 15.

With these parameters possible outcomes can be simulated using eq. 1. If a scenario tree is requested, then it is possible to use the same outcome up to a certain level, and then continue with different simulations. Figure 38 shows one example.

Correlation of wind speed forecast errors

When there are several sites with wind speed measurements, the corresponding measurement errors will be correlated according to, e.g., Figure 34. The method used here is then to simulate this with multidimensional ARMA-model. It can be noted that since the correlation increases with time in Figure 34, this means that the added uncertainty at different sites will be more similar when the forecast horizon increases. This means that the Z-variables in the ARMA series should have an increased correlation if an increased correlation between the resulting X-variables should increase. But it must though be noted that the correlations in Figure 34 are estimated from persistence forecasts, and it is not certain (but probable) that the structure of correlation between real forecast errors is the same. Should proper forecast error data become available, the

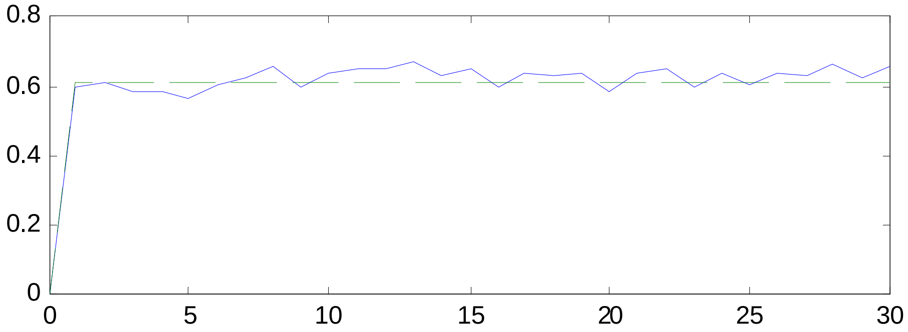


Figure 39: Correlation between two ARMA series; mean value of 200 outcomes of eq. 6 (straight line) and according to eq. 9 (dashed line). $\rho_{12}(k)=0.6080$.

procedure could be re-run to yield more realistic parameters. Below a method of how to obtain correlated simulated forecast errors is presented.

Correlation method

The method adds a correlated random variable to both parallel series. The assumption is here that the standard deviation of the common random variable is constant. Eq. 6 shows how this can be performed for two areas. The correlation between the two series is related to the size of the elements in the C-matrix.

$$\begin{aligned}
&X_1(0) = 0 \\
&Z_1(0) = 0 \\
&X_1(k) = \alpha_1 X_1(k-1) + Z_1(k) + \beta_1 Z_1(k-1) \\
&X_2(0) = 0 \\
&Z_2(0) = 0 \\
&X_2(k) = \alpha_2 X_2(k-1) + Z_2(k) + \beta_2 Z_2(k-1) \\
&Z_1(k) = c_{11} Z_{10}(k) + c_{12} Z_{20}(k) \\
&Z_2(k) = c_{21} Z_{10}(k) + c_{22} Z_{20}(k)
\end{aligned} \qquad (7)$$

where $Z_{10}(k)$ and $Z_{20}(k)$ are independent random Gaussian variables with standard deviations =1. The relations between the standard deviations are

$$\begin{aligned}
\sigma_{Z1}^2 &= c_{11}^2 + c_{12}^2 \\
\sigma_{Z2}^2 &= c_{21}^2 + c_{22}^2
\end{aligned} \qquad (8)$$

The covariance between $X_1(k)$ and $X_2(k)$ is defined as

$$C_{12}(k) = E\left[X_1(k) \cdot X_2(k)\right] \qquad (9)$$

The covariance $C_{12}(k)$ between $X_1(k)$ and $X_2(k)$ can now be calculated as

$$\begin{aligned}
&C_{12}(0) = 0 \\
&C_{12}(1) = E\left[X_1(1) X_2(1)\right] = E(Z_1 Z_2) = C(Z_1 Z_2) = c_{12} \cdot c_{21} + c_{21} \cdot c_{22} \\
&C_{12}(k) = \alpha_1 \alpha_2 C_{12}(k-1) + (1 + \beta_1 \beta_2 + \alpha_1 \beta_2 + \alpha_2 \beta_1) C(Z_1 Z_2)
\end{aligned} \qquad (10)$$

For $k \geq 2$, the expression for the covariance can be rewritten as

$$C_{12}(k) = C(Z_1 Z_2)\left(\left[\alpha_1 \alpha_2\right]^{(k-1)} + (1 + \beta_1 \beta_2 + \alpha_1 \beta_2 + \alpha_2 \beta_1) \sum_{i=1}^{k.1} \left[\alpha_1 \alpha_2\right]^{(i-1)}\right) \qquad (11)$$

The correlation can now be calculated as

$$\rho_{12}(k) = \frac{C_{12}(k)}{\sqrt{V_{X1}(k) \cdot V_{X2}(k)}} \qquad (12)$$

For a special case, when $\alpha_1 = \alpha_2 = \alpha$ and $\beta_1 = \beta_2 = \beta$, eqs. 3 and 11-12 become

$$\rho_{12}(k) = \frac{C_{12}(k)}{\sqrt{V_{X1}(k) \cdot V_{X2}(k)}} = \frac{C(Z_1 Z_2)}{\sigma_{Z1} \sigma_{Z2}} = \rho(Z_1 Z_2) \qquad (13)$$

i.e., the correlation between X_1 and X_2 is constant, independent of time, and it is equal to the correlation between the two noise variables Z_1 and Z_2. It can be noted that the standard deviations of the noises do not have to be the same, i.e., the variances of X_1 and X_2 do not have to be the same.

Eq. 7 can be rewritten in matrix form as

$$\begin{bmatrix} X_1(0) \\ X_2(0) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$
$$\begin{bmatrix} Z_1(0) \\ Z_2(0) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$
$$\begin{bmatrix} X_1(k) \\ X_2(k) \end{bmatrix} = \begin{bmatrix} \alpha_1 & 0 \\ 0 & \alpha_2 \end{bmatrix} \begin{bmatrix} X_1(k-1) \\ X_2(k-1) \end{bmatrix} + \begin{bmatrix} Z_1(k) \\ Z_2(k) \end{bmatrix} + \begin{bmatrix} \beta_1 & 0 \\ 0 & \beta_2 \end{bmatrix} \begin{bmatrix} Z_1(k-1) \\ Z_2(k-1) \end{bmatrix} \tag{14}$$
$$\begin{bmatrix} Z_1(k) \\ Z_2(k) \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} Z_{10}(k) \\ Z_{20}(k) \end{bmatrix}$$

which for a N-region system can be rewritten as

$$\begin{aligned} &[X(0)] = [0] \\ &[Z(0)] = [0] \\ &[X(k)] = [\alpha]\cdot[X(k-1)] + [Z(k)] + [\beta]\cdot[Z(k-1)] \\ &[Z(k)] = [C]\cdot[Z_0(k)] \end{aligned} \tag{15}$$

where

$[X(k)] =$ N-vector with forecast errors for hour k for the N regions

$[Z(k)] =$ N-vector with correlated noises for hour k for the N regions

$[\alpha] = N \times N$ diagonal matrix with the ARMA α parameters for the N regions

$[\beta] = N \times N$ diagonal matrix with the ARMA β parameters for the N regions

$[C] = N \times N$ matrix with connection parameters for the different Z_0-noises

$[Z_0(k)] =$ N-vector with independent noises for hour k for the N regions

Figure 39 shows an example of the correlation according to eq. 10 as a function of forecast length. In the figure the data are $\alpha_1=\alpha_2=0.97$, $\beta_1=\beta_2=-0.38$, $\sigma_{Z1}=\sigma_{Z2}=1.31$, $c_{12}=c_{21}=0.8$, $\sigma_{Z12}=1.28$

As shown in Figure 39, the correlation between $X_1(k)$ and $X_2(k)$ becomes constant with this approach. Parameter setting can control the level of the correlation.

Correlation method 2

The principal problem with the first method is the correlation becomes constant as shown in Figure 39. In reality the correlation increases, as shown in Figure 34. The second method is then to add a correlated random variable to both parallel series. In order to increase the correlation, the size of the common added random variable will increase and the independent added noise will instead decrease. Eq. 10 shows how this can be performed for two areas. The correlation between the two series is related to the size of the common $Z_{12}(k)$ variable, where the importance of this is controlled with the size of c_{12} and c_{21}.

This method is not yet fully developed. The idea is to get a model that give correlations according to Figure 34. It is not too complicated, since I have done slightly the same thing earlier.

5 Hydro data

Table 11 shows the Swedish and Norwegian hydro power capacities.

5.1 Inflow data

Available hydro inflow data

An overview over data used for the following hydro inflow analysis is shown in Table 10. The information from available observations is not enough to create the wanted inflow per region for a total of twenty years. Thus inflow, controllable inflow, uncontrollable inflow and flood per week for the years 1980-2000 are estimated for each region in Norway and for Sweden. The exactness of the estimations has been examined and the estimated values for Norway seem to be good both pr. region and total, while the estimated values for Sweden is not that good (see Figure 41 and Figure 43). If nothing else is mentioned the analysis is based on the observed data (from Nord Pool or SYKE).

Inflow is normally calculated as a function of increase in reservoir level and production for one week (n):

Inflow (n) = Reservoir (n+1)- Reservoir (n) – Production (n)

where reservoir level is the value in the beginning of the week.

Table 11: Hydro power production and reservoir capacity in Norway and Sweden.

Region:	Installed hydro power production capacity:	Reservoir capacity:
SE (total)	16.753 MW	33.758 GWh
SE_N	15.530 MW	30.651 GWh
SE_M	1.121 MW	2.869 GWh
SE_S	102 MW	238 GWh
NO (total)	27.500 MW	81.729 GWh
NO_S		55.975 GWh
NO_M + NO_N		25.754 GWh

Table 10: Available data (country, regions and time periods).

Data:	Country	Region	Years	Source
Inflow pr. week	NO	No regions	1995-2003	Nord Pool
Inflow pr. week	SE	No regions	1995-2003	Nord Pool
Inflow pr. day	FI	-	1978-2003	Finish Environment Institute SYKE (via Nord Pool)
Reservoir levels pr week	NO	NO, NO_S and NO_M+N	1998-2003	SSB
Reservoir capacity	NO and SE	SE (all regions) NO, NO_S, NO_M+N	2002	SSB and KTH
Estimated inflow, controllable inflow, uncontrollable inflow, flood and reservoir levels	NO and SE	SE, NO, NO_S, NO_M+N	1980-2000	SINTEF

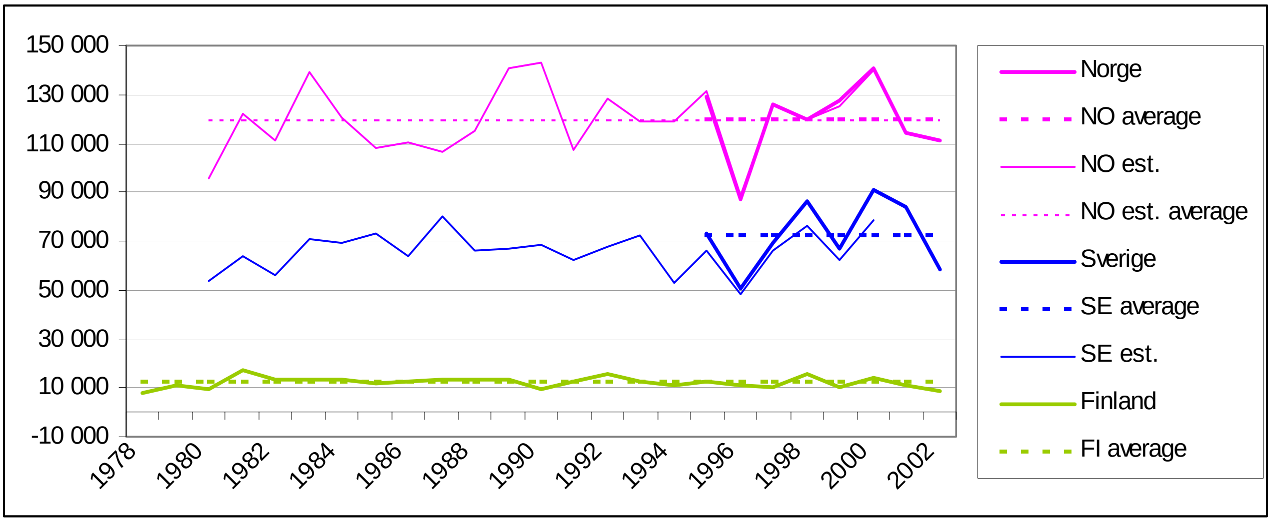


Figure 40: Yearly inflow pr. country [GWh/year]. Data from NordPool (bold lines) and estimated data for Norway and Sweden from 1980 – 2000 (thin lines). Average values are dotted.

Inflow pr. year

Variations in yearly inflow in the Nordic countries are shown in Figure 40 and Figure 41. In average the inflow situation is as follows (the time period of the observations is shown in brackets):

- Average Nordic inflow is 204 TWh/year, min. 150 and max. 247 TWH/year (1995-2002).
- Norwegian inflow is 59 %, Swedish 35 % and Finish 6 % of the yearly Nordic inflow.
- Average Finish inflow is 12 TWh/year, min. 8 and max. 17 TWh/year (1978-2003).
- Average Swedish inflow is 73 TWh/year, min. 51 and max. 91 TWh/year (1995-2002).
- Average Norwegian inflow is 120 TWh/year, min. 87 TWh/y and max. 143 TWh/y (both estimated and with data from 1995-2002).
- Yearly inflow of each Swedish region is: SE_S 1 %, SE_M 8 % and SE_N 91 % (KTH).
- Yearly inflow of each Norwegian region is: NO_S 73 %, NO_M 19 % and

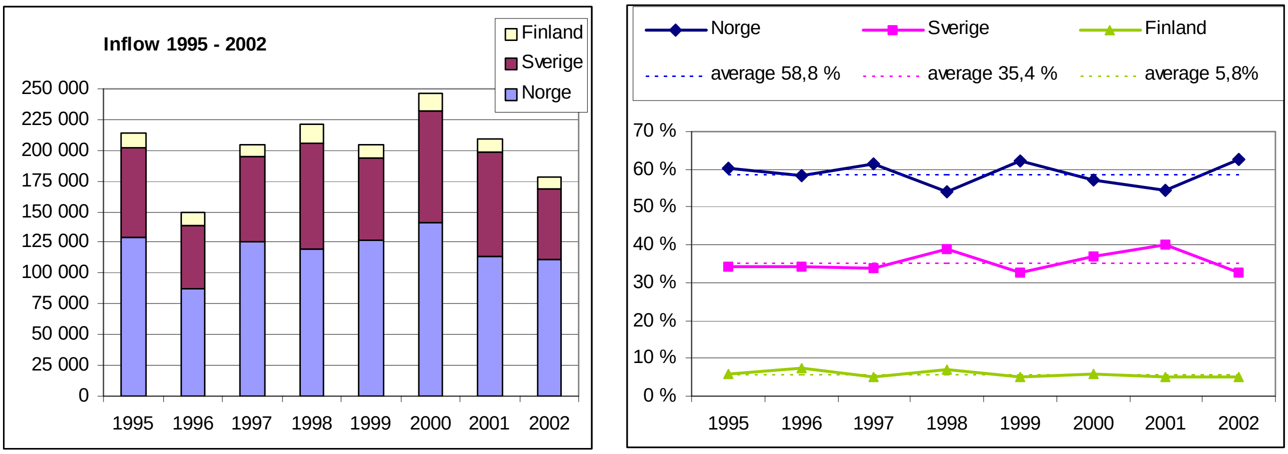


Figure 41: Total Nordic inflow for the years 1995 – 2000 in GWh/year (left), and % of total (right).

Table 12: Extreme values of weekly inflow pr. year [GWh/week] given exact week and year.

Country	Lowest minimum	Highest minimum	Lowest maximum	Highest maximum
Nordic total (1995-2002)	155 (w12/1996)	1119 (w13/2000)	9662 (w23/1996)	22347 (w22/1995)
FI (1978-2002)	46 (w36/1997)	125 (w9/1992)	634 (w21/1990)	1532 (w21/1995)
SE (1995-2002)	74 (w21/1996)	385 (w11/2000	3253 (w25/1996)	9773 (w22/1995)
NO (1995-2002)	5 (w12/1996)	587 (w13/2000)	5689 (w23/1996)	11435 (w22/1995)
NO estimated (1980-00)	178 (w12/1980)	528 (w51/1989)	6254 (w23/1987)	11831 (w22/1983)

NO_N 8 % (estim.).

Weekly inflow and variations over the year

Figure 43 shows average inflow, together with minimum and maximum values pr. week for all countries. Note that the maximum and minimum curves represent values observed the given week of the year, and consist of observations from different years.

Figure 43 also shows the exact weekly inflow in each country for four interesting years:

- 1995: Very high weekly inflow in week 21 and 22 - Nordic inflow 215 TWh (105 % of av.).
- 1996: Very low yearly inflow and low maximum inflow in week 21, 23 and 25 – Nordic inflow 150 TWh (73% of average).
- 2000: High yearly inflow, but no extremely high weekly inflo values – Nordic inflow was 247 TWh (121 % of average inflow).
- 2002: Low inflow in the autumn high in the summer but no extreme values – Nordic inflow was 178 TWh (87 % of average inflow).

Reservoir levels

Figure 42 show reservoir level in Norway in percent of total reservoir capacity, which is 81729 GWh.

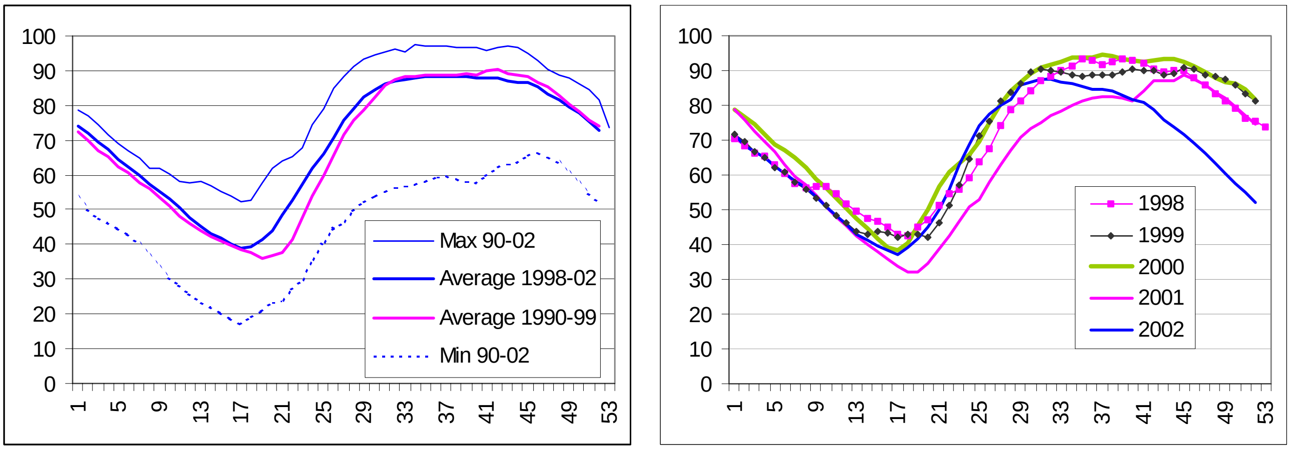


Figure 42: Observed reservoir levels in Norway in percent of total reservoir capacity. Left: Max and min levels for the period 1990-02, together with average values for two different time periods. Right: Weekly variations of the years 1998-2002.

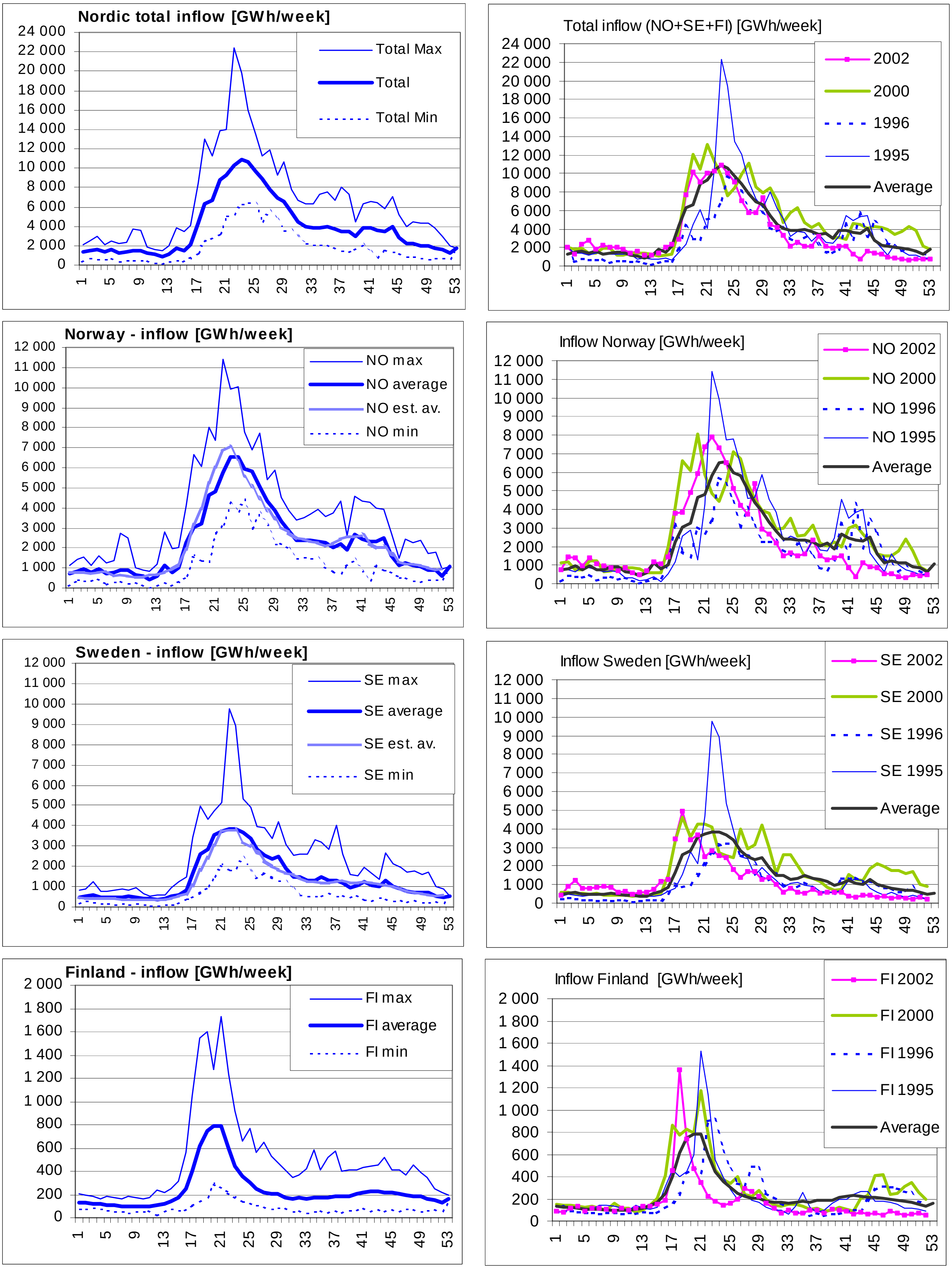


Figure 43: Left: Average, minimum and maximum inflow pr. week. Right: Weekly and average inflow of the years 1995, 1996, 2000 and 2002. Yearly average inflow [TWh/year]: Nordic total 205, NO 120, SE 73, FI 12.

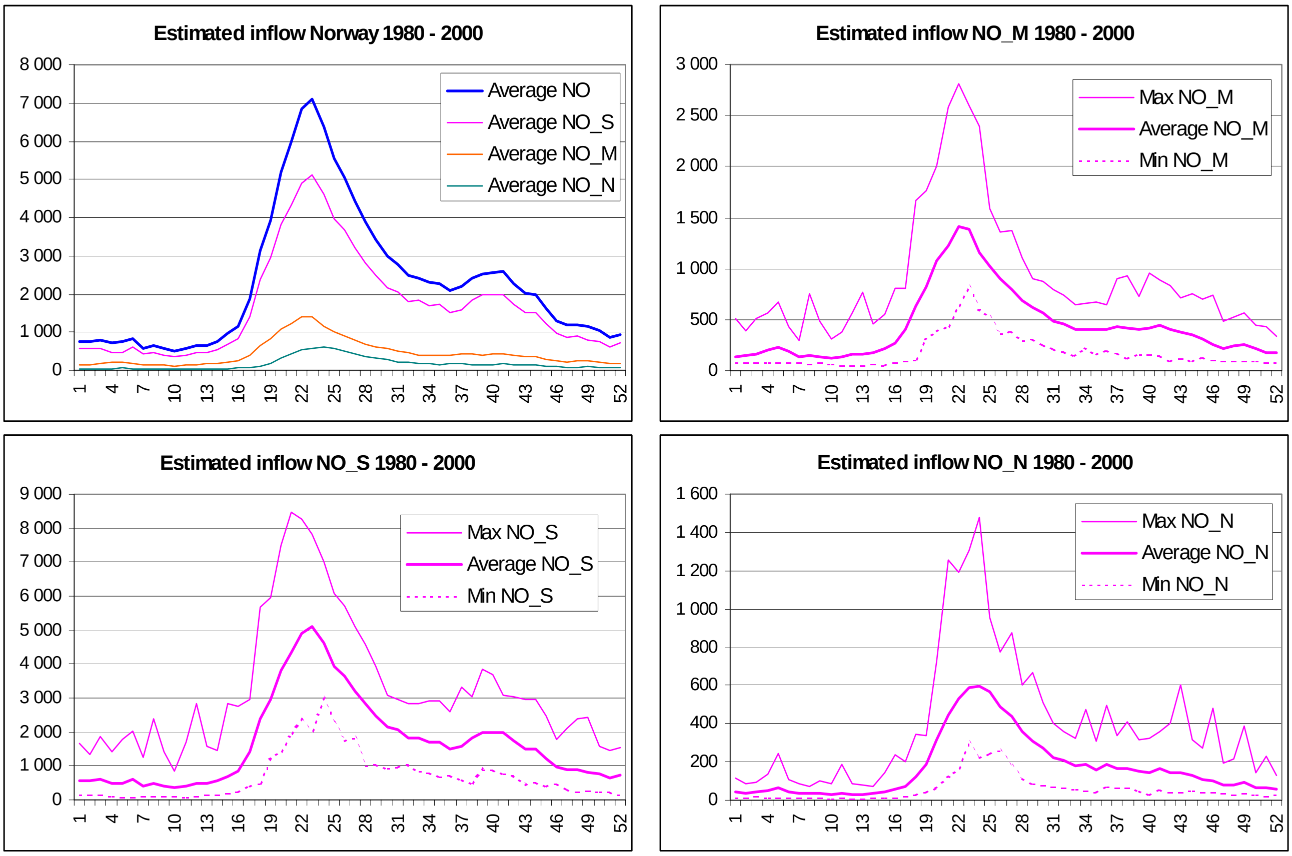


Figure 44: Inflow in the Norwegian regions shown as weekly average, min. and max. values.

5.2 Differences between regions

The Swedish weekly inflow is divided between the regions with the same in each region as for the yearly inflow: SE_S 1 %, SE_M 8 % and SE_N 92 % (information from KTH).

In Norway the division of the weekly inflow between the regions varies, as shown in Table 13. Figure 44 shows the average inflow (with maximum and minimum) of each region. This information is based on estimations.

5.3 Controllable, uncontrollable inflow and flood

The estimations of the Norwegian hydro inflow situation give information of controllable inflow, uncontrollable inflow and flood in each region. Inflow is the part that is useful for power production:

Inflow = Controllable inflow + Uncontrollable inflow - Flood

Table 13: Extreme values of weekly inflow pr. region in percent of weekly total inflow (1980-00).

Region:	Lowest weekly %	Average %	Highest weekly %
NO_S	28 %	73 %	94 %
NO_M	4 %	22 %	56 %
NO_N	1 %	8 %	29 %

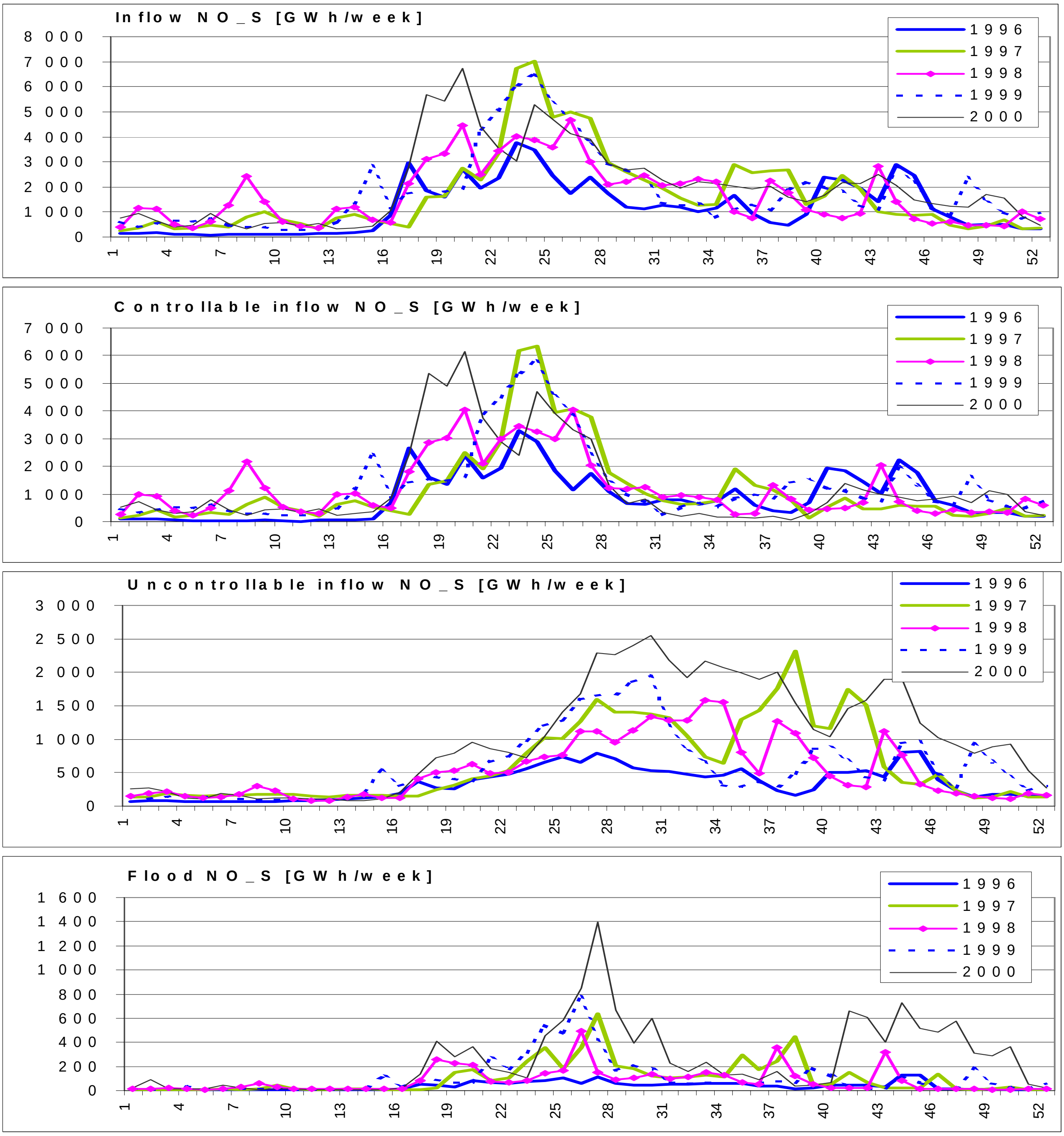


Figure 45: Weekly inflow, controllable inflow, uncontrollable inflow and flood in Norway for the years 1996 - 2000.

Figure 46 shows the estimated yearly average for the Norwegian regions both in GWh/year and in % of inflow within each region. The controllable part of the yearly inflow is 70 % in NO_S and as much as 86 % in NO_N. In Norway the average controllable inflow is 86 TWh/year (72 % of the 120 TWh/year average inflow), the average uncontrollable inflow is 43 TWh/year (36 % of average inflow) and the flood is 9,5 TWh/year (8 % of average inflow).

Figure 45 show the weekly variations and correlations of inflow, controllable and uncontrollable, and flood for the years 1996 – 2002 (all estimated values).

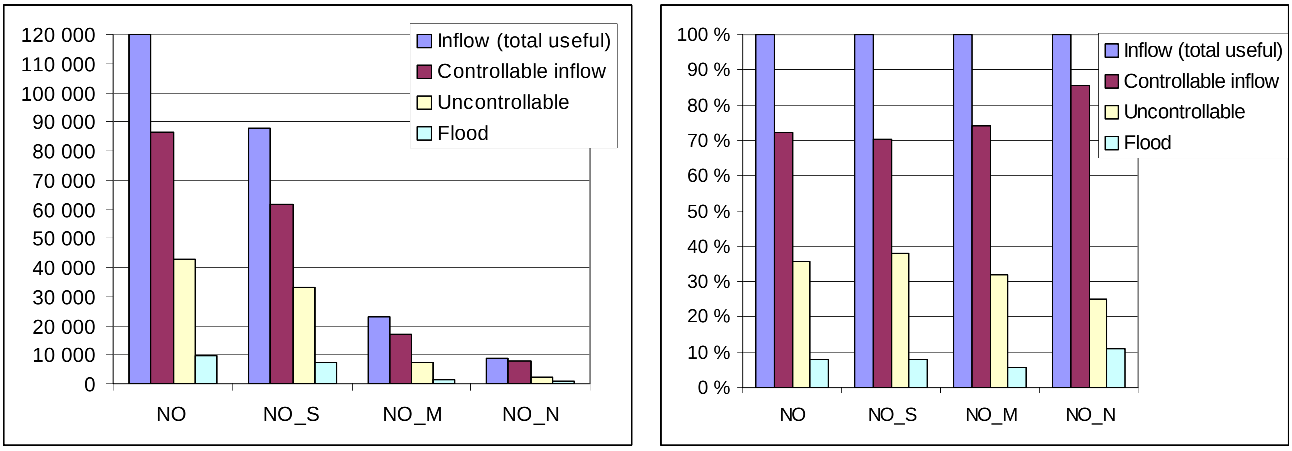


Figure 46: Yearly average inflow, controllable, uncontrollable and flood in the NO regions. Left: GWh/year. Right: % of inflow within the region.

6 Correlation between wind/hydro/temperature

6.1 Temperature dependence of wind power production and load

In Figure 47 to Figure 50, the temperature dependence is depicted for Finland and Denmark, as well as for the Nordic wind power as the function of Finnish temperature. The average wind power production at low temperatures of below –15 °C is somewhat lower than average in Finland, and these are the incidents of highest load (Figure 47). The average wind power production in Denmark as well as the total Nordic wind power does not experience this kind of reduction (Figure 49).

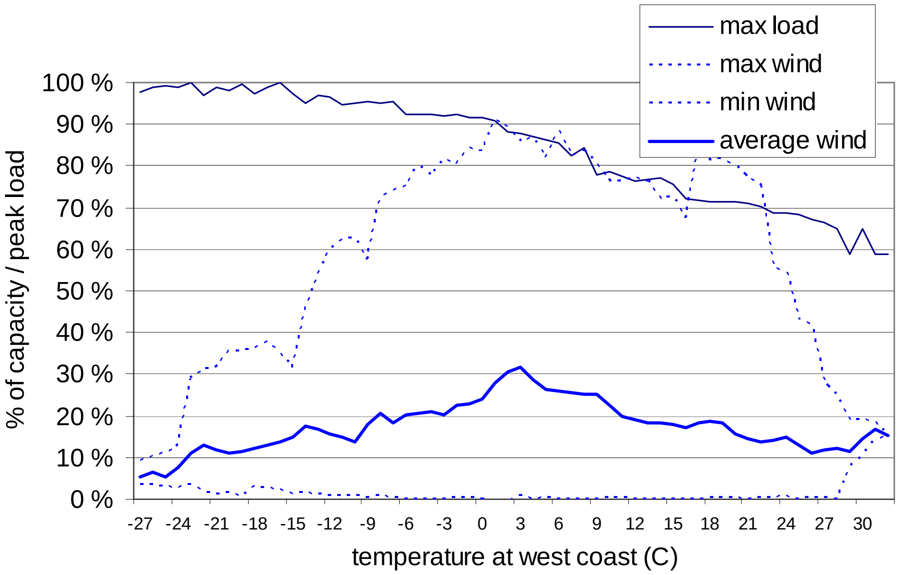


Figure 47: Temperature dependence of wind power production and load in a cold climate, example from Finland. There were 48 hours (0.1 % of time) below –23 °C and 549 hours (1.6 % of time) below –14°C during the study years 1999-2002.

Table 14. Table temperature correlation of load and wind power production in the Nordic countries, hourly data from 2000-2001

	FI temperature	DK East temperature	NO temperature
FI temperature	1,00		
DK East temperature	0,88	1,00	
NO temperature	0,88	0,82	1,00
FI load	-0,63	-0,56	-0,57
SE load	-0,72	-0,68	-0,69
NO load	-0,79	-0,76	-0,79
DK load	-0,25	-0,21	-0,27
Nordic load	-0,72	-0,67	-0,69
FI wind	-0,09	-0,11	-0,11
SE wind	-0,18	-0,14	-0,20
NO wind	-0,32	-0,32	-0,28
DK wind	-0,13	-0,07	-0,15
Nordic wind	-0,32	-0,32	-0,28

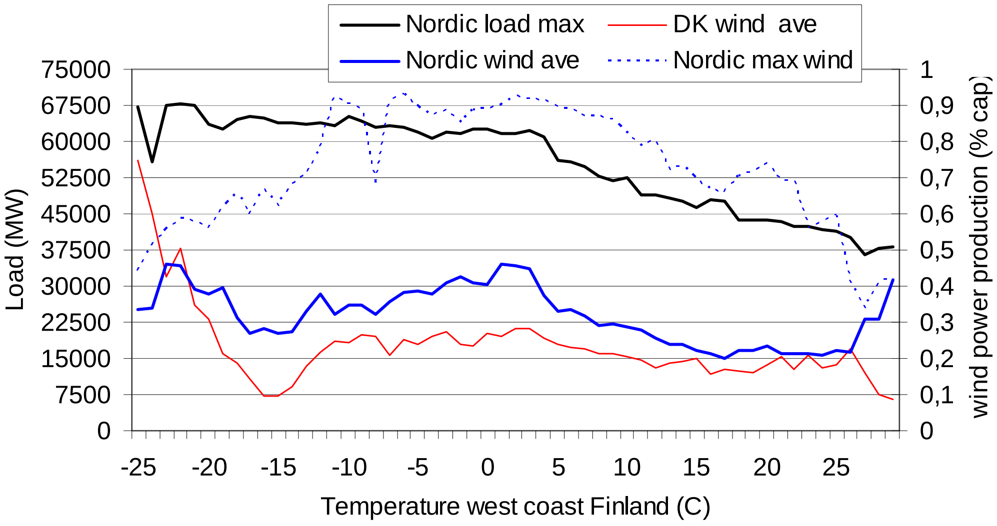


Figure 49: Wind power production and load in Nordic countries as a function of temperatures in Finland. Years 2000-2001.

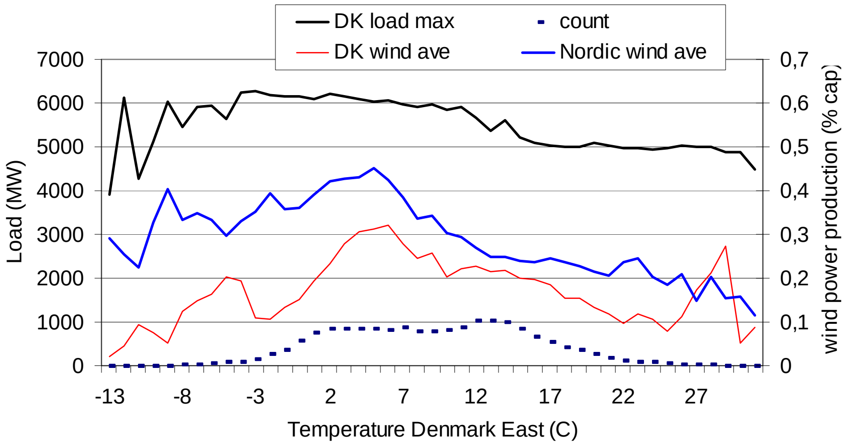


Figure 50: Temperature dependence of wind power production and load in Denmark. Years 2000-2001.

6.2 Correlation of hydro inflow and wind power production

Hydro inflow is very season dependent. In the Nordic countries, there is hardly any inflow during the winter, and a huge inflow during late spring when the snow is melting. As hydro power operates in most cases with large reservoirs, evening out the large seasonal variation of inflow, the short term correlation of hydro inflow and wind power is not very relevant for power system operation. However, the yearly correlation of wind power and hydro power can have influence in wind power integration. If the correlation was negative, the dry years would have a tendency of being windy years, and this would be beneficial for the integration.

Previous studies have suggested that wind power and hydro power production are weakly correlated in same area, like North Sweden (Söder, 1999), but correlation is near zero for other sites in Nordic countries (Holttinen et al, 2001). These are based on hydro production data, which is slightly different than the actual inflow data used here, as there are also large, inter-annual reservoirs in Norway and Sweden. Here, yearly inflow data from the years 1980-2002 was used.

Table 15. Correlation between wind and hydro resource: yearly wind index and hydro inflow time series of 1980-2002.

	FI wind index	SE wind index	DK wind index	FI inflow	SE inflow	NO inflow
FI wind index	1.00					
SE wind index	0.58	1.00				
DK wind index	0.50	0.66	1.00			
FI inflow	0.48	0.21	0.30	1.00		
SE inflow	0.04	0.03	0.04	0.38	1.00	
NO inflow	0.52	0.68	0.43	0.24	0.45	1.00
NO_S inflow	0.41	0.70	0.48			
NO_M inflow	0.57	0.49	0.29			
NO_N inflow	0.46	0.17	-0.11			

The correlations between hydro and wind resources is presented in Table 15. Wind resource data was represented by wind production indices from national wind energy statistics (Laakso, 2003; Carlsted, 2003; Naturlig energi, 2003).

According to this data, the Swedish inflow is not correlated with wind power production in the Nordic countries, whereas the Norwegian inflow is correlated with the Swedish wind power production, and also with the Finnish and Danish, although weakly. The Finnish inflow is correlated, weakly, with Finnish wind power production. Looking more detailed, dividing Norway into 3 regions, it is the South Norway inflow that has the correlation with wind power production in Sweden, and weak correlation to Danish winds. North Norway inflow is correlated (weakly) with Finnish wind power production and Middle Norway inflow is correlated (weakly) also with Swedish winds.

6.3 Example years 2000-2002 compared to long term average

Table 16. Wind power production, hydro inflow and temperature in years 2000, 2001 and 2002 compared with long term average (1987-2002 for wind power, 1980-2002 for hydro inflow and 1996-2002 for temperature).Temperature data from towns Copenhagen, Stockholm, Helsinki and Trondheim.

		2000	2001	2002
Wind	DK	95 %	80 %	95 %
	SE	102 %	88 %	98 %
	FI	97 %	87 %	76 %
Hydro	SE	116 %	89 %	71 %
	NO	117 %	96 %	93 %
	FI	136 %	124 %	86 %
Temp	DK Cph	111 %	101 %	101 %
	SE Sto	129 %	118 %	125 %
	FI Hel	142 %	118 %	121 %
	NO Tro	129 %	98 %	121 %

7 Final remarks

As output of WP 2 will serve as input for the further work in the WILMAR project, the data collection, the analyses and the model development will still continue. The end-of-project status will be finally reported and documented at the end of the project.

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Annex

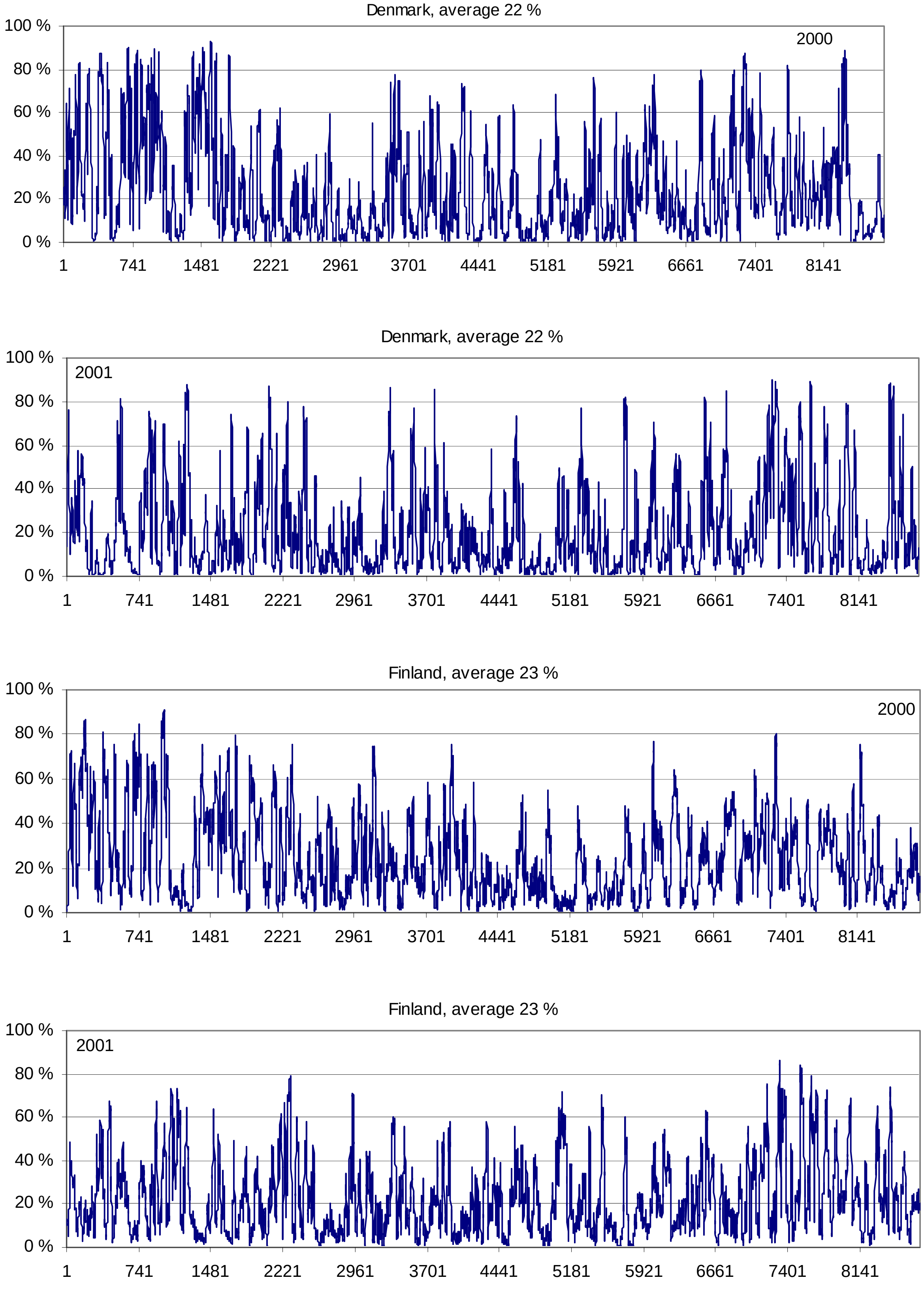


Figure 51. Hourly wind power production time series for Denmark and Finland, example years 2000 and 2001. The production values as % of capacity (y-axis). On x-axis, the hour of the year is marked at 740 hour (about one month) intervals.

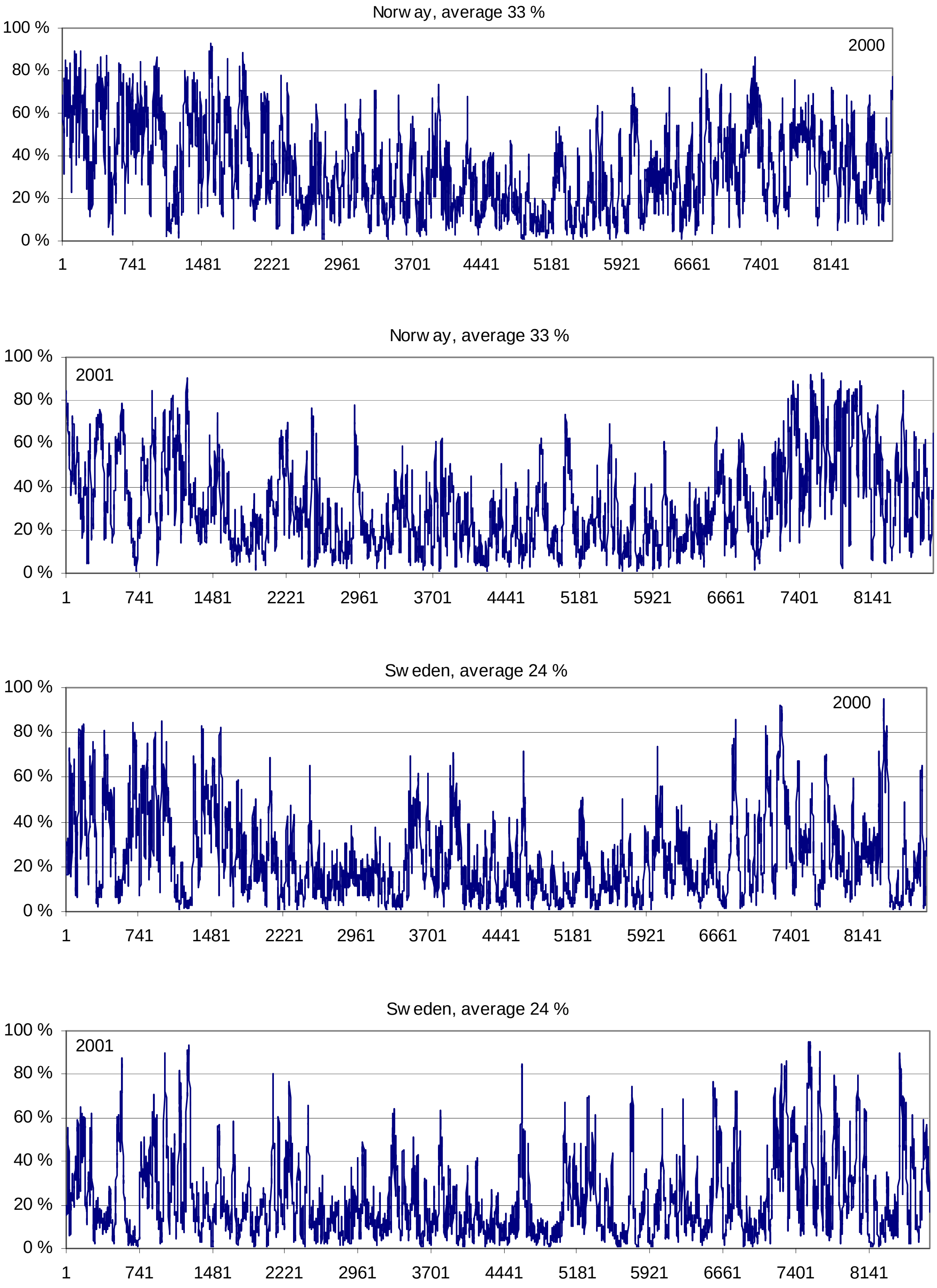


Figure 52.Hourly wind power production time series for Norway and Sweden, example years 2000 and 2001. The production values as % of capacity (y-axis). On x-axis, the hour of the year is marked at 740 hour (about a month) intervals.

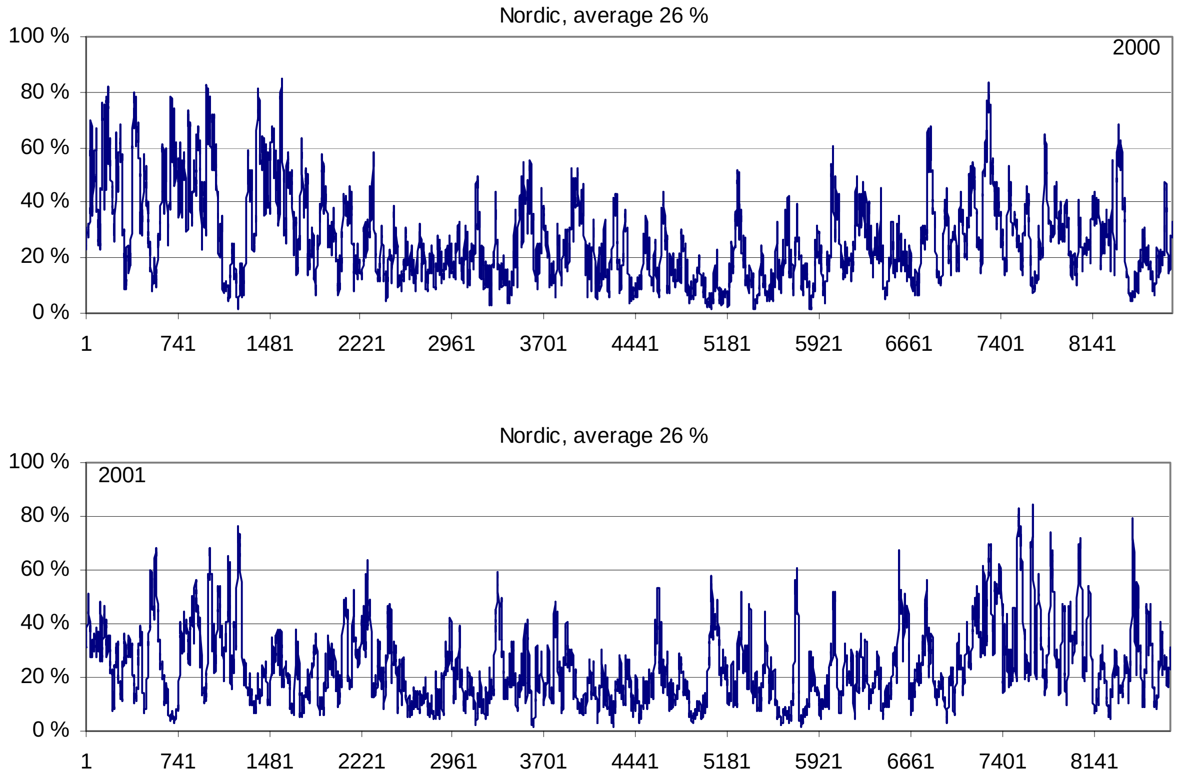


Figure 53. Hourly wind power production time series for example years 2000 and 2001, assuming same capacity in all 4 countries Sweden, Norway, Denmark and Finland. The production values as % of capacity (y-axis). On x-axis, the hour of the year is marked at 740 hour (about a month) intervals.

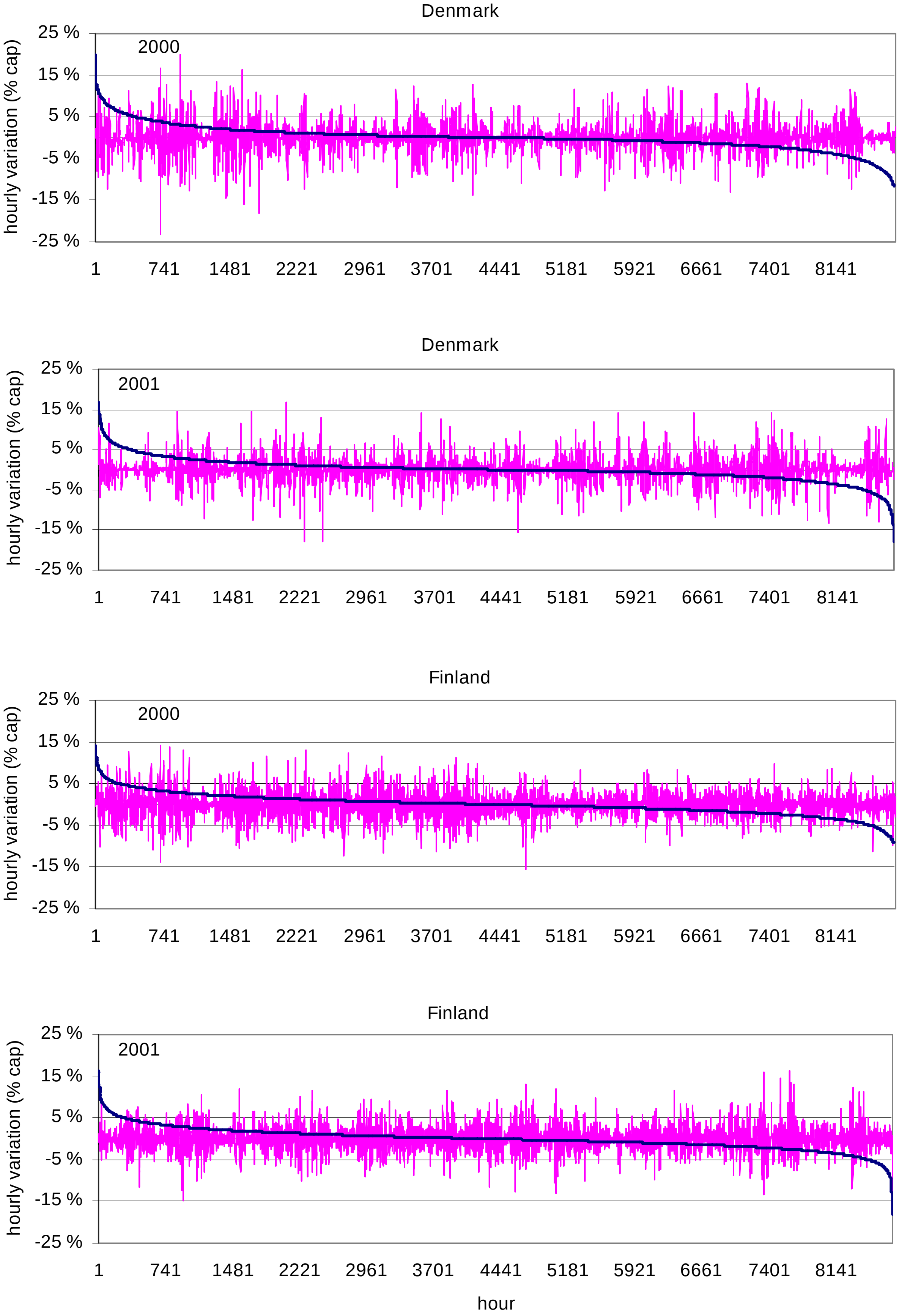


Figure 54.Time series for hourly variations of wind power production for Denmark and Finland, example years 2000 and 2001. Positive means increasing and negative decreasing wind power production.

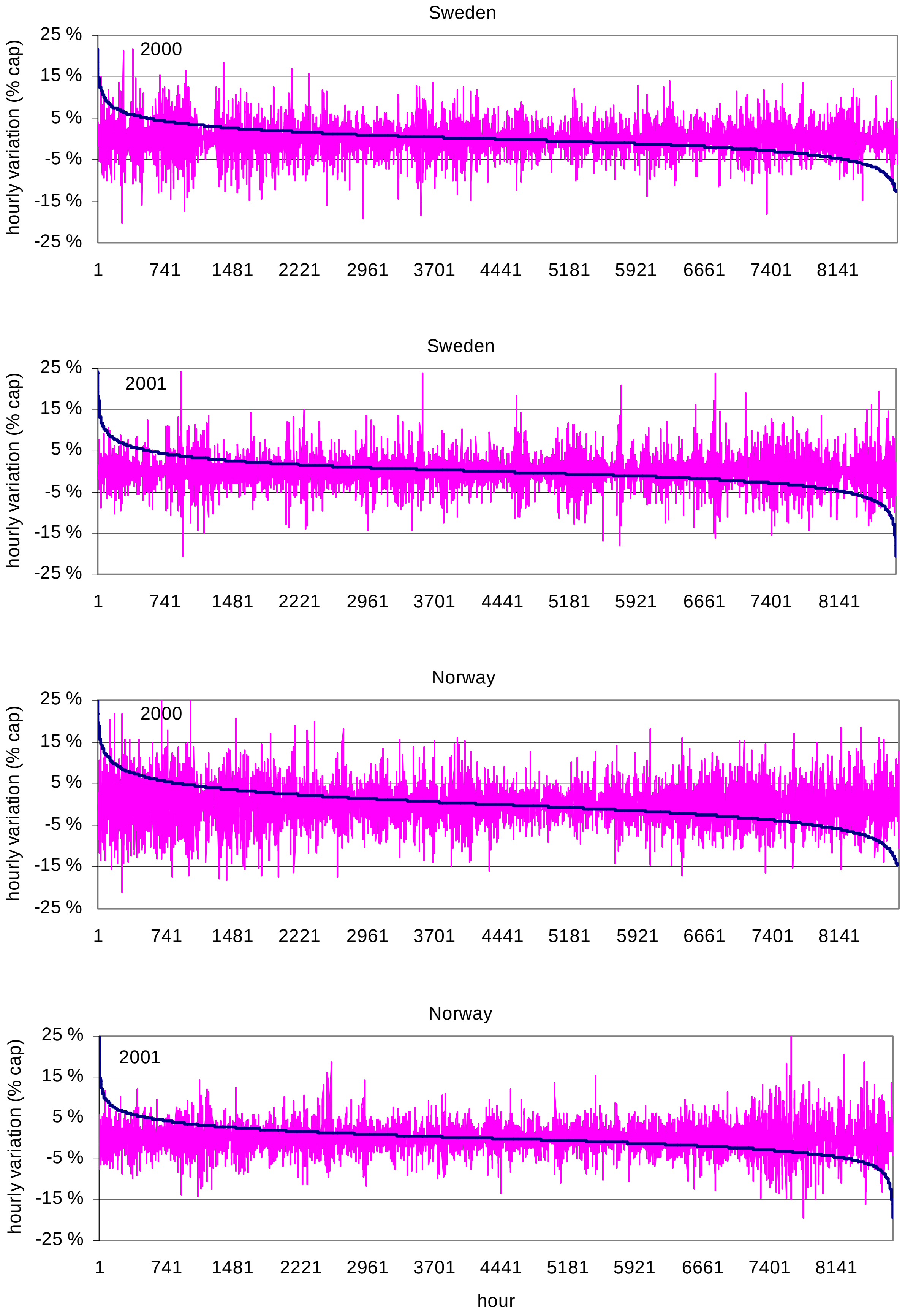
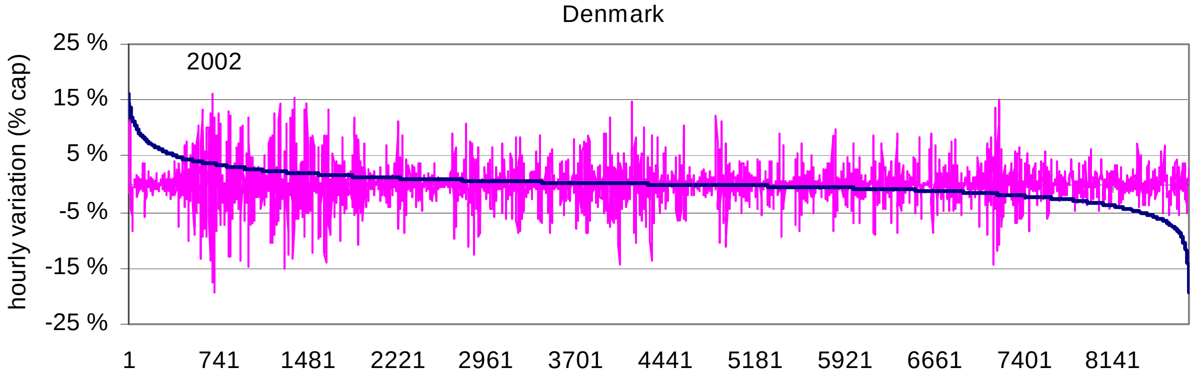


Figure 55: Time series for hourly variations of wind power production for Sweden and Norway, example years 2000 and 2001. Positive means increasing and negative decreasing wind power production.


Denmark
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2002
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5 %
-5 %
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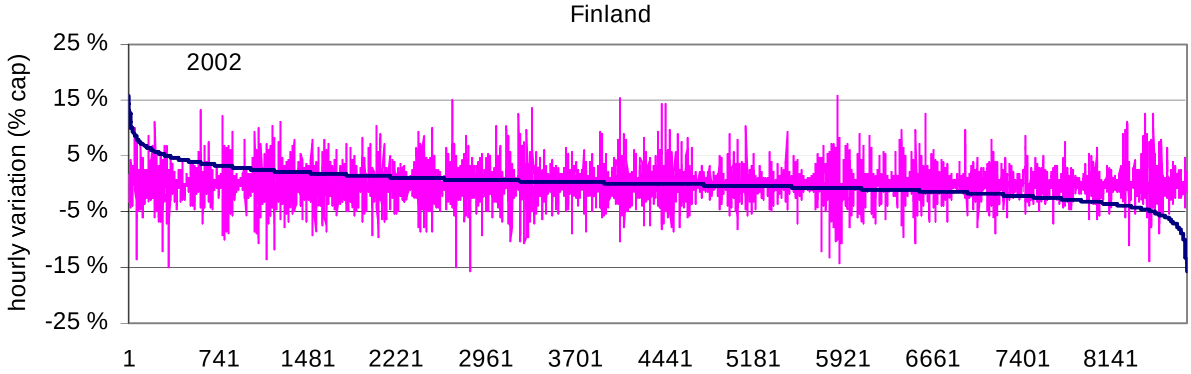
Finland
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2002
25 %
15 %
5 %
-5 %
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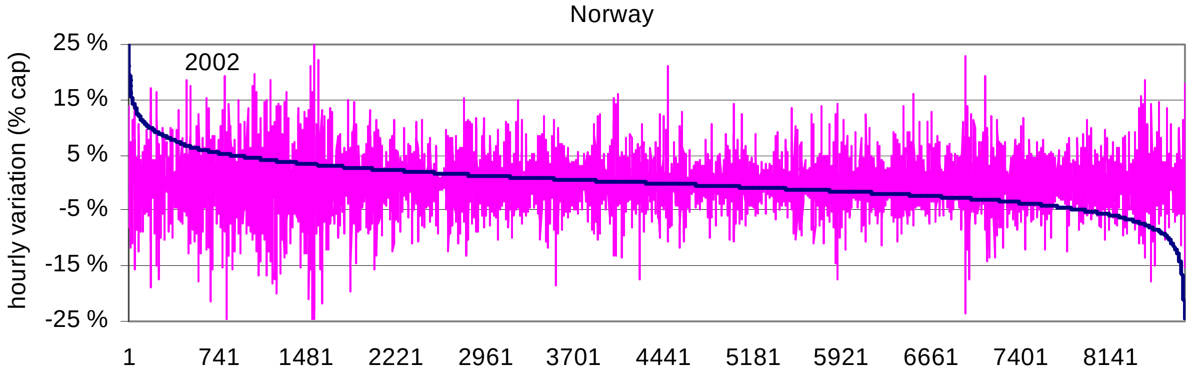
Norway
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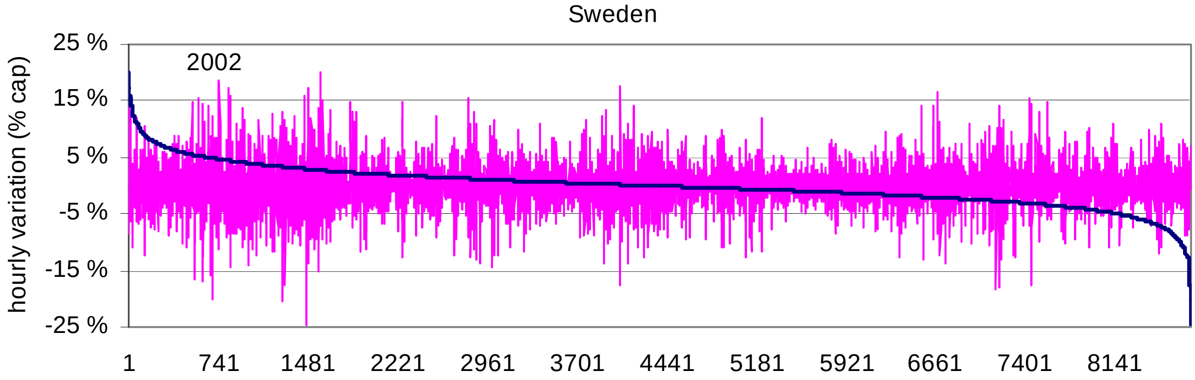
Sweden
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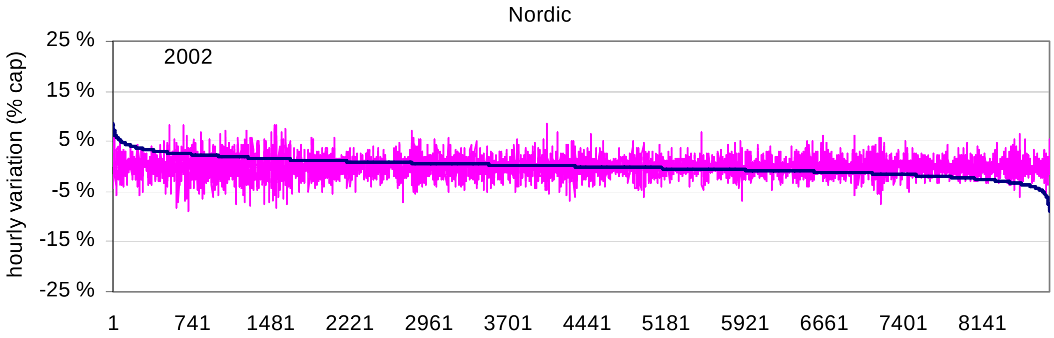

Figure 56.Time series for hourly variations in Denmark, Finland, Norway, Sweden and the combination of the four, example year 2002. Positive means increasing and negative decreasing wind power production.

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