Technical University of Denmark

Equalizing effects of the wind energy production in Northern Europe determined from reanalysis data

Giebel, Gregor

Publication date:
2000

Document Version
Publisher's PDF, also known as Version of record

Risø-R-1182(EN)

Equalizing Effects of the Wind Energy Production in Northern Europe Determined from Reanalysis Data

Gregor Giebel

Risø National Laboratory, Roskilde
May 2000

Abstract The wind energy resource of Northern Europe is spread out over a geographically large area. This helps the integration of wind energy into the grid, since the generation is less variable, when it is combined from a larger area. The analysis was done based on 34 years of Reanalysis data. A short overview of the resource is given. The main analysis deals with the smoothing stemming from the averaging of multiple time series from many sites in the Nordic countries and south of the Baltic/North Sea.

ISBN 87-550-2698-2 (Print)
ISBN 87-550-2754-7 (Internet)
ISSN 0106-2840

Information Service Department, Risø, 2001

Contents

Preface

This report is part of a larger study on the wind power characteristics in Northern Europe, done for the Transmission System Operators in Denmark. The aim of this part is to show the variability, but also the smoothing effects associated with high wind power penetration in Northern Europe.

Internal review by: Henrik Bindner, VEA

1 Introduction

This study will analyse to which extent the wind energy generation in Northern Europe is correlated, and to which extent the geographic dispersion of generation smoothes the overall generation. The sources used are two scenarios of installed wind energy capacity for the year 2020, and the wind speed derived from the NCEP/NCAR reanalysis project [Reanalysis].

The reanalysis project is an effort to run state-of-the-art weather models on historical meteorological data. The aim here is to create one consistent data set without artificial trends that were introduced at a model change. In the US effort, most meteorological observations from 1948 to present day were used to create one consistent model run, using the same data assimilation procedure and the same meteorological model throughout and hence create one consistent time series spanning the whole globe for five decades. The model used a T62 spectral triangular Gaussian grid with a resolution of about 2°x2° horizontally and 28 levels vertically. The data used here was from 1965 to 1998, 12-hourly 10-minute averages of wind speed at 10 m height a.g.l. This means that in all, 24836 data points in time were used.

The methodology to get a common wind energy production from reanalysis wind speeds was as follows:

Firstly, the wind speed was transformed to the wind speed in 80m height, using a roughness of 10 cm and no orography or roughness related speed-up. In the case of Poland and Germany, this led to far too low Full Load Hours (FLH) for the turbines. As can be seen from Figure 1, the resource in most of Poland and in the continental part of Germany is rather low, so that there would be no wind installations unless the local conditions would enhance the resource. In these countries, an orography speed-up of 15% was assumed, as well as a hub height of 100 m. Using these "fudge factors", it was possible to calculate a mean wind speed which would see investment in wind turbines, and to increase the wind power output to a level consistent with the data.

The next step was to fold the resulting wind through the power curve. From WAsP's library of power curves, the Nordex N54 with 1000MW_{peak} was chosen. Since the power production was scaled up to the values given in the scenarios, it was felt that the small relative differences in power production from a smaller number of larger turbines would not influence the results very much.

As a final step, the resulting time series were multiplied with the installed capacity assumed in the scenarios, and added up. This was done either on a per-country basis, or for all time series from the Nordic countries (DK, NO, SE, FI), or for all time series available. The check was then performed whether the calculated FLH were reasonable (before tweaking, Germany and Poland had a Load Factor (LF) of as low as 5%). According to [Wind Force 10], the average LF of wind turbines has increased from 0.2 to 0.25 over the last years. Since most of the capacity assumed is still to be built, it is safe to assume that the LF of these new installations would be even higher. However, the LF is a variable to be decided when building the turbine, and in some cases, the optimisation of the turbine for high yield at low cost can mean a lower LF, even though the overall production is higher [HuttingClejne].

Table 1: The scenarios for wind energy installation in Northern Europe in 2020. LF=Load Factor, #=Number of grid points in that country.

[illegible]nario 1				Scenario 2
Installed	LF	#	Country	Installed
3700 MW	0.25213	5	Denmark	7000 MW
1600 MW	0.25165	15	Norway	4000 MW
3500 MW	0.25678	26	Sweden	8000 MW
1000 MW	0.2535	16	Finland	2000 MW
1000 MW	0.19644	12	Poland	2000 MW
5000 MW	0.26493	11	Germany	10000 MW
2000 MW	0.29194	2	Holland	5000 MW
600 MW		2	Belgium	2000 MW
18400 MW	0.2691	89	Sum	40000 MW

One problem with the grid points of the reanalysis data can be seen from Table 1: Due to the nature of the grid, which is equidistant in degrees, there are more grid points per area in the north than in the south of the area in question. This means that while northern Norway or northern Sweden is quite well covered, Belgium and Holland only have 2 points to deal with. (The exact distribution of installed power to grid points is given in Appendix A.) This should not constitute a big problem, but one has to keep in mind that the averaging effects of correlated time series are more pronounced with the number of series. Therefore, one would assume that even with the same spatial variation of the wind speed in the north as in the south, the averaging effects of the south are underestimated.

Note here that scenario 2 is mainly a (more than) doubling of installed capacity. Therefore, it is used explicitly only where absolute numbers are important. Since the amount of data points available from reanalysis is fixed, and the relative weight of the different countries is rather similar, most of this study is done for scenario 1 only. Eg, the smoothing effects are only dependent on the number of data points and their relative weights, and not on the absolute numbers. Therefore, for most purposes the difference between the scenarios is just a scaling.

2 The Resource

Currently, no wind atlas is available for Sweden and Finland. Even though some work leading to it has been done, the work is not finished yet. The same applies for the wind atlas for the Baltic Sea. However, to get an impression of the resource, the wind speed at 10m height was averaged for every year available from reanalysis. Shown here is the year with the production closest to the average production of all years, which is 1978.

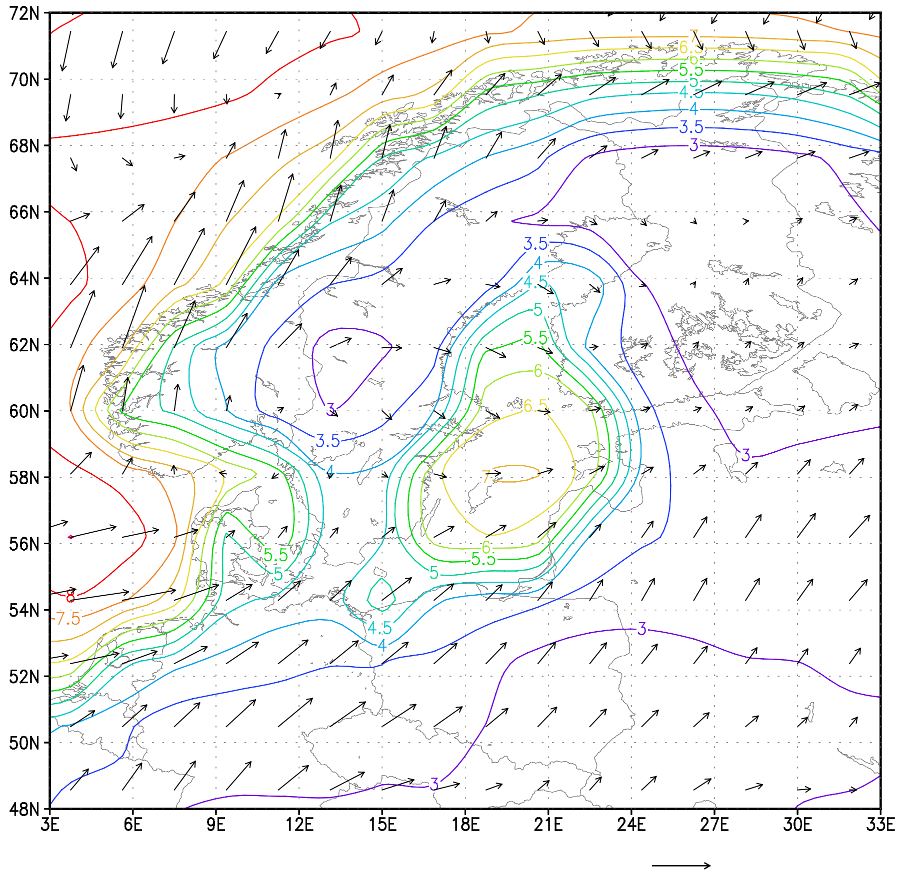

Figure 1: The wind resource of Northern Europe in m/s at 10m height, averaged from Reanalysis data for 1978. The arrows are the mean wind vector at every Reanalysis grid point.

In Figure 1 the wind resource is shown for 10m height. This wind speed should not be taken as absolute, since it has to be transformed to the hub height of the prospective turbine, using the logarithmic height profile [WAsP manual] and the proper roughness and orography assessment for the site. Keep in mind that the power in the wind is proportional to the wind speed to the third. Local effects like mountains or low roughness areas can significantly enhance the resource, so even though in central Finland the wind speed is only 3 m/s, on a hill top in hub height the resource can be significantly higher, making an investment viable.

Another point of interest is the variability of the resource in different years. This analysis has been done for the power output from 83 grid points in Northern Europe with the available data for scenario 1 (Figure 2). The result shows differences of some 15% up and down from year to year.

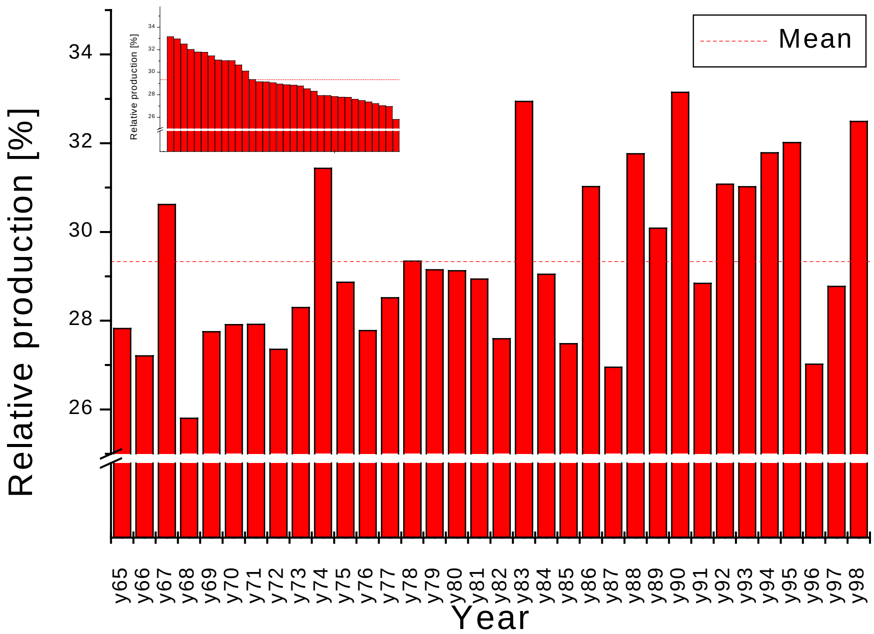

Figure 2: Mean wind power production in Northern Europe for 34 years as a percentage of installed capacity. In the inset: the same graph, ordered by size.

3 Equalisation Effects

When combining the generation of variable sources, an averaging effect occurs, if the time series of the generators are uncorrelated or only partly correlated. For an analysis of this behaviour, Figure 3 shows the cross-correlation of all pairs of grid points. For Figure 4, only the Nordic countries are shown. A correlation coefficient of 1 means that the time series are perfectly correlated, and hence go up and down in exactly the same fashion. A coefficient of 0 means that the time series are randomly distributed. The results differ slightly from country to country: the cross-correlation in Sweden for example falls faster with distance than the one in Norway. A reason could be that Norway is hit by weather fronts (typically coming over via the North Sea) more or less all at once, while Sweden with its larger east west distance has fronts travelling across.

The exponential fit in Figure 3 has an effective distance (for the decay to 1/e) of 840 km. This is in the same range as for all of Europe [Giebel].

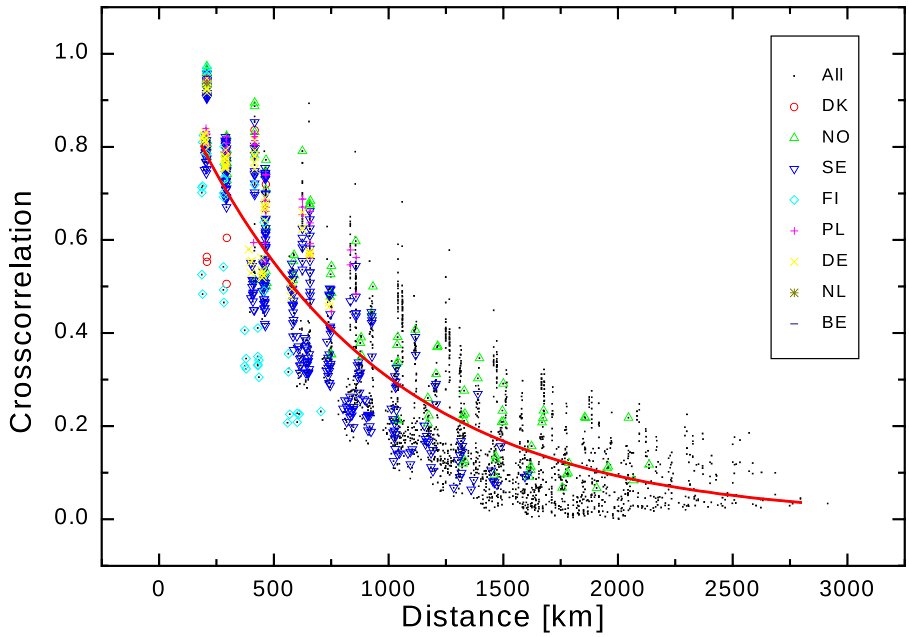

Figure 3: Cross-correlation versus distance between grid points. The full line is a fit of an exponential decay. Each country is plotted alone in the appendix for better clarity.

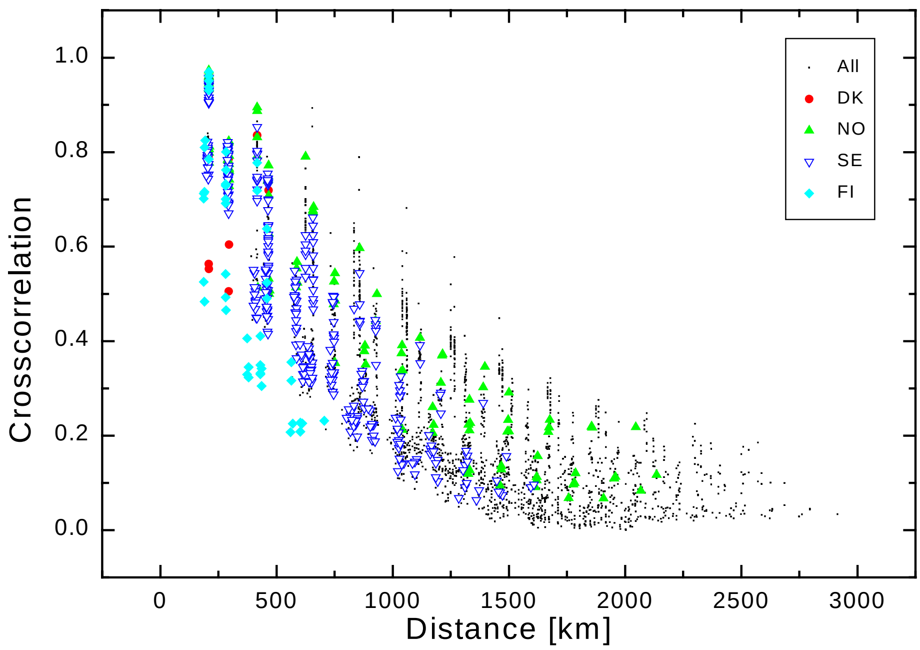

Figure 4: Same as Figure 3, for the Nordic countries only.

Another important graph to show the smoothing effects comes from the 250MW Wind programme in Germany. In Figure 5, 5-minute averages were used and aggregated to longer averaging times. The cross-correlation coefficient of the changes from one time step to the next is displayed for averaging times of 5 minutes, 30 minutes, 1 hour, 4 hours and 12 hours. The correlation coefficient of the changes between one-hour averages falls rather rapidly with distance and is below 0.2 already for few tens of kilometres. This is to say that for an area as

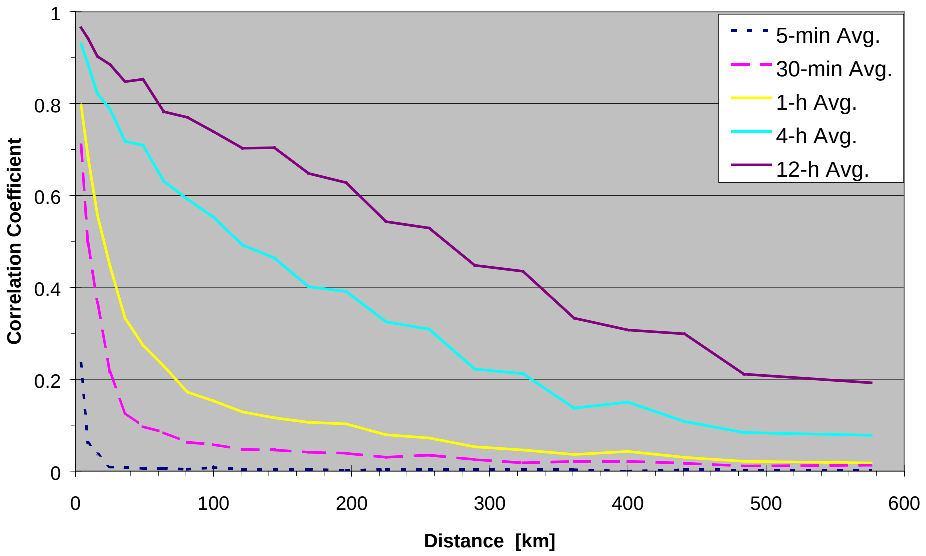

Figure 5: Cross-correlation of changes in turbine power for different averaging times in Germany. Source: [Ernst]

large as Northern Europe, the wind power production is changing on a scale of a few hours, and there are relatively few significant changes faster than one hour.

A similar behaviour can be seen from Figure 6. The changes on a scale of 12 hours (which is the data resolution available from reanalysis) are not even for the case of Denmark very pronounced. For Denmark, the frequency of occurrence for the loss of 25% or more of rated power output over a 12-hour period was 8.1%. This is actually better seen from Figure 7. For the most extreme events, one could guess that the shape of the curve can be drawn out by hand to yield up to 100% change, with a probability for a change from full power to zero within 12 hours in Denmark of ca 10^{-6} (ie, one event every many hundred years). With 730 changes in a year, the probability density of an event occurring once a year is $1.37 \cdot 10^{-3}$. Therefore, the largest change typically occurring once a year in Northern Europe can be estimated to be about ±30% of the installed capacity. Please keep in mind here that all these numbers are indicative and should mostly be used for comparison against each other. However, it is easy to see that the overall variation encountered in the larger area is smaller than in Denmark alone. Interestingly enough, the additional spreading of the resource south of Denmark does hardly account for much additional smoothing. The probable reason is that the number of data points is too low in the south.

The same feature can be found in the generation duration curve in Figure 8. The curve for Denmark alone is more variable (steeper) than the curve for the Nordic countries and northern Europe as a whole. The difference between the latter, however, is relatively small.

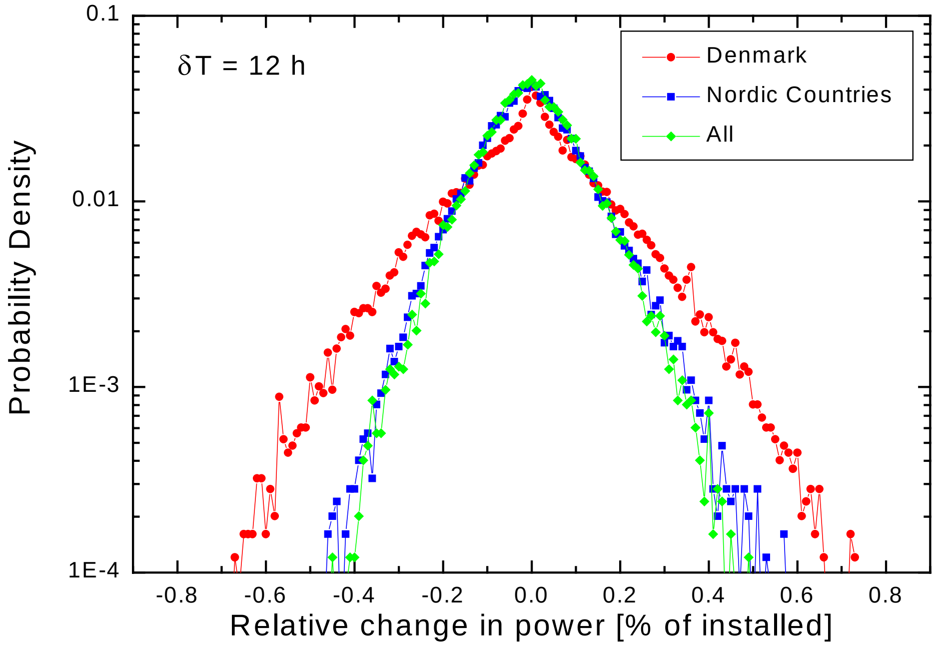

Figure 6: Frequency of changes in lumped power output. The x-axis is normalised to installed capacity. Please take notice of the logarithmic y-axis. A loss of exactly 20% of installed power in the whole area over a 12-hour period has a probability of 0.75%.

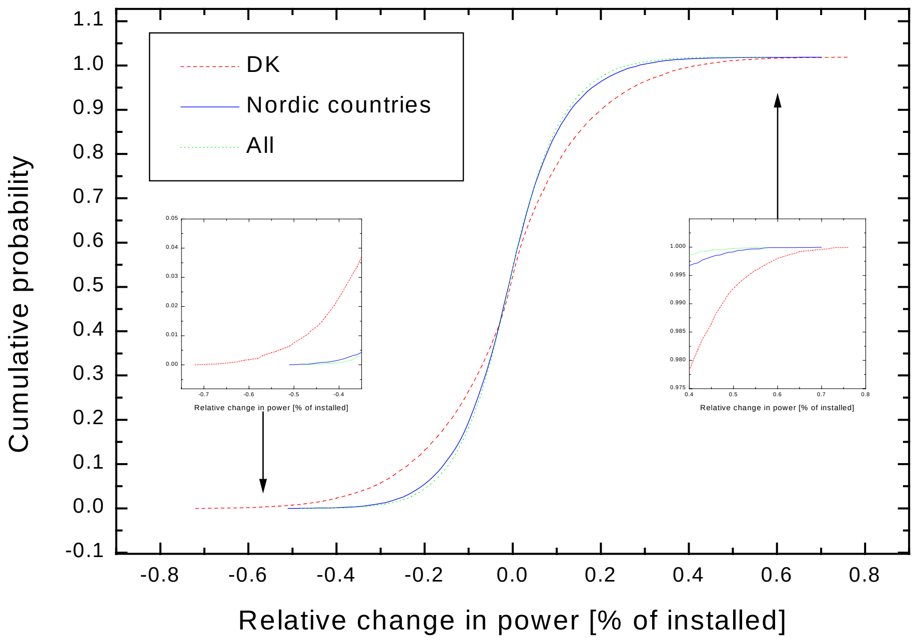

Figure 7: Cumulative frequency of changes. The lines are integrated from the numbers in Figure 6. A loss of 20% or more in Denmark occurred in 12.9% of all cases. In the insets: zoomed in on the beginning and end of the curves.

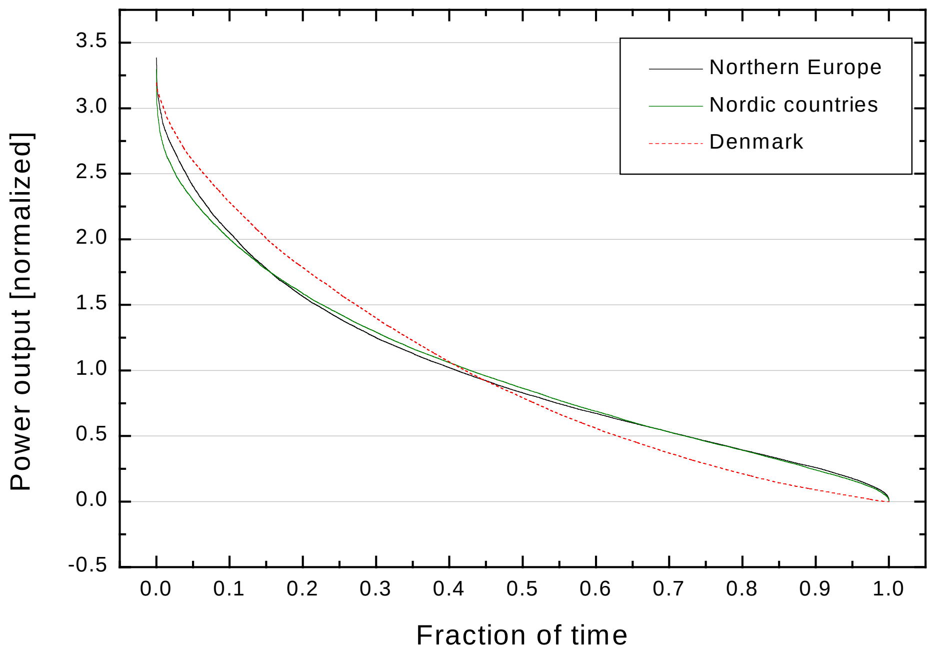

Figure 8: Wind energy generation duration curve for Northern Europe, the Nordic countries combined and for Denmark alone. The power output is normalised to its mean production.

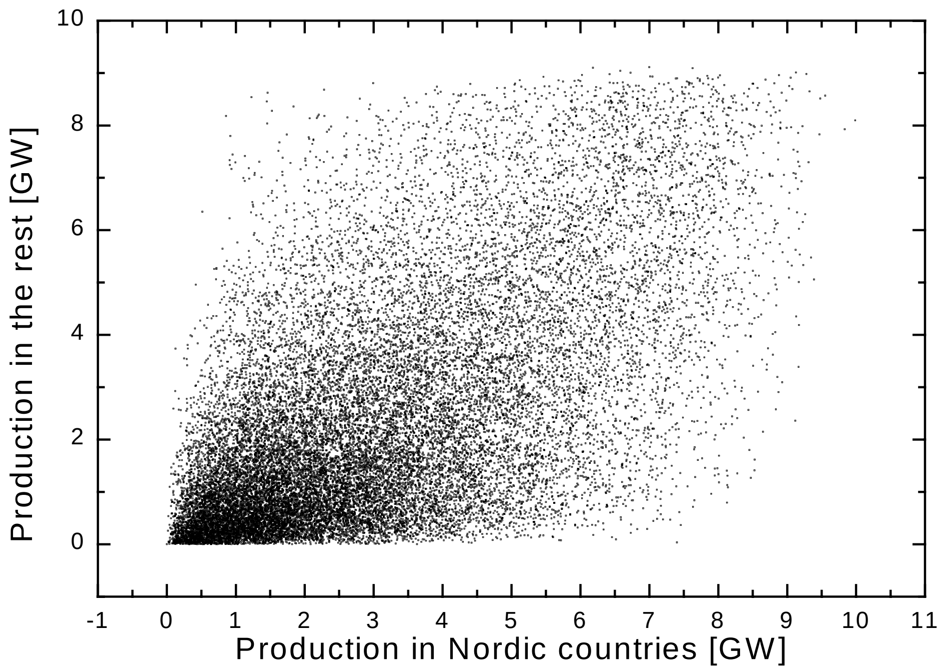

Figure 9: Production in the rest of the area over production in the Nordic countries for each hour of the time series.

For quite a wide range of production in the Nordic countries the production in the rest of the analysed area the production can be zero. Or, to state it the other way round: when the combined production of Holland, Belgium, Germany and Poland is zero, the production in the Nordic countries can reach up to more than half of the installed capacity. Please keep in mind that there are significantly less reanalysis grid points in the south: 62 are in the north, while only 27 grid points were in the south. Since the standard deviation of the resulting time series is defined[1] by $\sigma=\Sigma(\sigma_i*\sigma_j*corr(i,j))$, the more times series one takes into account, the better the smoothing effect, since the same installed capacity will be distributed on more sites. This means that the smoothing effect in the South is not equal to the smoothing in the North. Both are probably underestimated.

The production in the south is more heavily weighted towards relatively low values. This behaviour has its reason in the relatively low resource and the partly great distance from oceans, where local weather systems can be more pronounced.

The most important feature of Figure 9 is the absence of features. This means that there is only a slight correlation between the generation south of Denmark and the generation in the Nordic countries. This trend is to see at high production in the Nordic countries: then the production seems to be high for all of Northern Europe. The only real trend is the strong representation of low generation from the remaining area for less-than-half generation in Nordic countries. However, with the generation duration curve lingering mostly in the lower third of the production curve, and with overall load factors of 25-30%, it is not surprising to find most of the data cramped in the lower left corner.

The frequency of power transmission through Denmark is shown in Figure 10. Actually, this is not really the need for power transmission - it is the relative distribution of generation north and south of Denmark. This is to say that changes in demand and other power generation in the region of generation are not considered. It could very well be that in many cases all of the generated wind energy can be accommodated within the respective region. On average, 570 MW are unbalanced and might have to be transported northwards. The most frequent case, however, is to transport a few hundred MW southwards. In the extreme cases, ca 95% of the installed capacity in the South (DE+BE+NL+PL=8600MW) has to be transported northwards, while only about 70% of the installed capacity of the North (NO+SE+FI=6100MW) is not balanced.

---

1 σ is the standard deviation of the resulting time series, σ_i and σ_j are the standard deviations of the single time series, and corr(i,j) denotes the correlation coefficient between the series i and j.

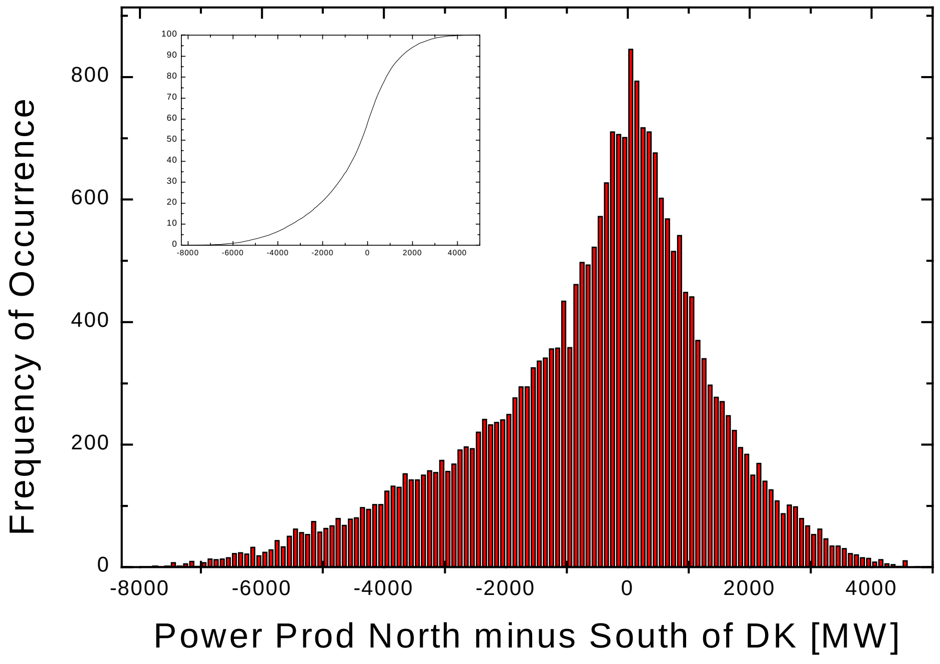

Figure 10: Frequency distribution of the relative power production north and south of Denmark. For positive numbers, the power flows southwards. In the inset: the cumulative distribution. The numbers are events in the total time series of 24836 data points.

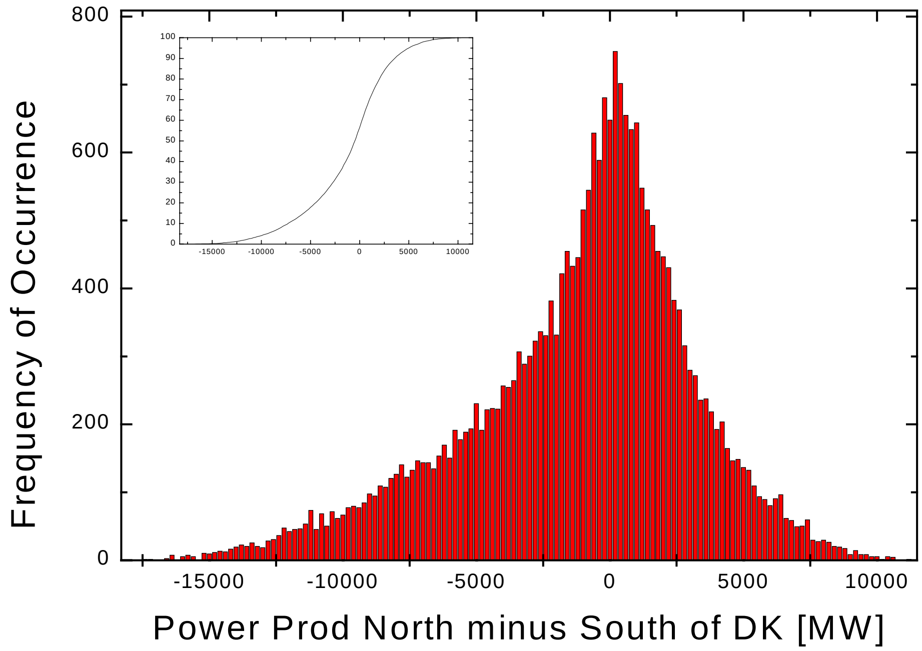

Figure 11: Same as Figure 10, but for scenario 2. Apart from overall higher numbers, the difference is rather small.

In Figure 11, the power transmission demand distribution is calculated for the installed capacities assumed in scenario 2 (see Table 1). The same disclaimers apply as in the previous paragraph. The mean here is slightly more than 1100 MW.

The combined production is shown in Figure 12. Some features are noteworthy: the production in the summer never even reaches 80% of the installed production, while close to full production can occur in the winter. These events occur rather infrequently. Furthermore, keep in mind that a technical availability of 100% is assumed here implicitly, since any other assumption would introduce an additional level of uncertainty in this fairly theoretical exercise. During winter, however, there is always some production online, even though it is not much. During summer, nearly no production can be relied upon. Keep in mind, too, for both the maximum and minimum generation shown here, that it is based on few points per country. In a real life situation, the generation would come from many thousands of turbines, creating just by the large numbers a somewhat smoother generation than assumed here.

Another interesting point is that the average production does have some daily variation in the summer months. An analysis of the data reveals that the scatter visible in the summer occurs on a time scale of 12 hours (the higher production is at 1200 hours UTC, ie midday), while the scatter during winter has a time scale of a few days. Note also that even though the average over the 34-year period is looking quite smooth, the single-year time series are scattered over the whole area.

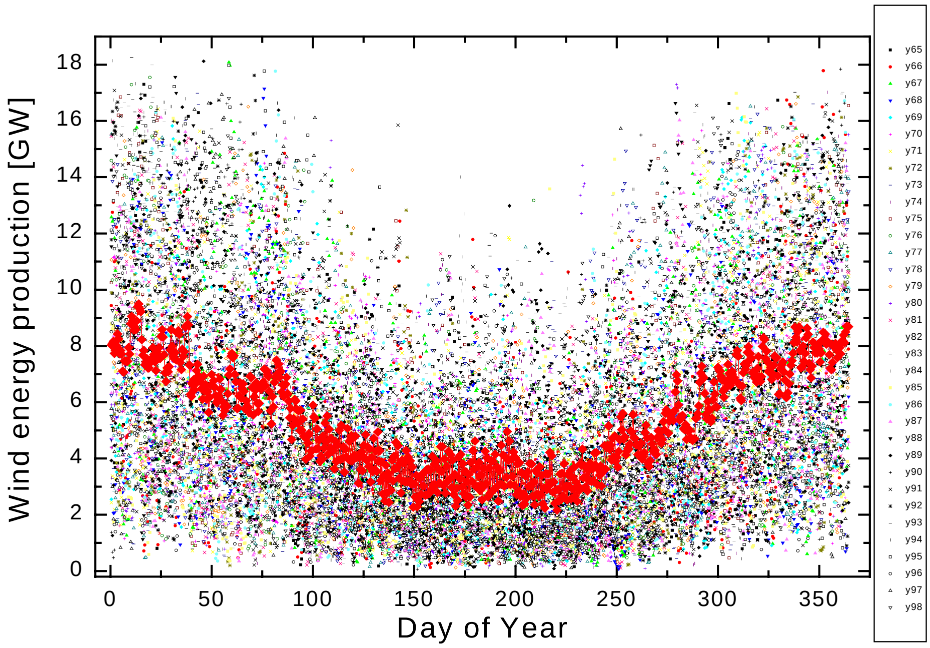

Figure 12: Average wind power production of northern Europe. The single time series denoted in the legend are the time series of combined production in the single years, while the red diamonds denote the average production for every time step during the 34-year period analysed.

4 Conclusion

The distribution of wind energy generation over an area as large as Northern Europe is beneficial for the continuity of the supply. Wind power generation from sites with a distance of more than 1500 km is nearly uncorrelated. This leads to a smoothing of wind power production. Changes on a time scale of one hour are relatively small, while changes on a time scale of 12 hours can reach ca. ±30% about once a year. The additional spread of wind power generation to Northern Germany and Poland does not contribute much to the smoothing;

however, this might be an artefact of the grid spacing used by reanalysis. The total annual production of the whole area can vary by ca. ±15% from year to year. While close to full power can occur in winter, the maximum power found for the summer months is below 80% of the installed capacity. There is always a small percentage of capacity running in winter, while no capacity can be relied upon during summer. Within the scenarios used here, the mean generation is higher south of Denmark than north, while the most frequent imbalance occurs for higher generation north of Denmark.

5 Literature

[Ernst] Bernhard Ernst, Diplomarbeit: *Short-Term Power Fluctuations of Wind Turbines from the Ancillary Services Viewpoint*, Institut für Solare Energieversorgungstechnik e.V., Querschnitts-Projektbereich Windenergie (Mittlerweile: Forschungsbereich Information und Energiewirtschaft). (1999) Kassel, Germany.

[Giebel] Gregor Giebel, PhD-Thesis: *On the Benefits of Distributed Generation of Wind Energy in Europe*. Carl von Ossietzky Universität Oldenburg, 2000

[HuttingClejne] Hutting, H.K., and J.W. Cleijne: *The Price of Large Scale Offshore Wind Energy in a Free Electricity Market*. Proceedings of the European Wind Energy Conference, Nice, France, 1-5 March 1999, pp. 399-401, ISBN 1 902916 00 X

[Reanalysis] Kalney, E. et al.: *The NCEP/NCAR 40-year reanalysis project*. Bulletin of the American Meteorological Society **77** (1996), p. 437-471. See also http://wesley.wwb.noaa.gov/reanalysis.html

[WAsP manual] Mortensen, N.G., L. Landberg, I. Troen, E.L. Petersen: *Wind Atlas Analysis and Application Program (WAsP) - User's Guide*, Risø-I-666(EN)(v.2), Risø National Laboratory, Roskilde, Denmark, 133 pp.

[Wind Force 10] *Wind Force 10*, EWEA, Forum for Energy and Development, Greenpeace International, 1999, ISBN 1 871532 248

6 Appendix

List over installed capacity in scenario 1 at every grid point

Name	Longitude	Latitude	Installed [MW]
Denmark:			
DK01	9.375	54.289	950
DK02	11.25	54.289	600
DK03	9.375	56.194	950
DK04	11.25	56.194	600
DK05	7.5	56.194	600
Norway:			
NO01	7.5	58.099	150.0
NO02	5.625	60.004	150.0
NO03	7.5	60.004	150.0
NO04	9.375	60.004	150.0
NO05	5.625	61.909	90.91
NO06	7.5	61.909	90.91
NO07	9.375	61.909	90.91
NO08	11.25	63.814	90.91
NO09	13.125	65.719	90.91
NO10	15	67.624	90.91
NO11	16.875	67.624	90.91
NO12	16.875	69.529	90.91
NO13	18.75	69.529	90.91
NO14	20.625	69.529	90.91
NO15	22.5	69.529	90.91
Sweden:			
SE01	13.125	56.194	500.0
SE02	15	56.194	500.0
SE03	13.125	58.099	1.0
SE04	15	58.099	1.0
SE05	11.25	60.004	1.0
SE06	13.125	60.004	1.0
SE07	15	60.004	1.0
SE08	16.875	60.004	1.0
SE09	11.25	61.909	66.67
SE10	13.125	61.909	66.67
SE11	15	61.909	66.67
SE12	16.875	61.909	66.67
SE13	13.125	63.814	66.67
SE14	15	63.814	66.67
SE15	16.875	63.814	60.67
SE16	18.75	63.814	66.67
SE17	15	65.719	66.67
SE18	16.875	65.719	66.67
SE19	18.75	65.719	66.67
SE20	20.625	65.719	66.67
SE21	18.75	67.624	66.67
SE22	20.625	67.624	66.67
SE23	22.5	67.624	66.67
SE24	11.25	58.099	500.0
SE25	16.875	58.099	500.0
SE26	18.75	60.004	500.0
Finland:			
FI01	22.5	61.909	50.0
FI02	24.375	61.909	50.0
FI03	26.25	61.909	50.0
FI04	28.125	61.909	50.0
FI05	24.375	63.814	50.0
FI06	26.25	63.814	44.0

FI07	28.125	63.814	1.0
FI08	26.25	65.719	50.0
FI09	28.125	65.719	1.0
FI10	28.125	67.624	1.0
FI11	26.25	67.624	1.0
FI12	26.25	69.529	1.0
FI13	28.125	69.529	1.0
FI14	20.625	61.909	300.0
FI15	22.5	60.004	300.0
FI16	24.375	60.004	50.0
Northern Poland:			
PL01	16.875	54.289	125.0
PL02	18.75	54.289	125.0
PL03	20.625	54.289	125.0
PL04	22.5	54.289	125.0
PL05	16.875	52.384	62.5
PL06	18.75	52.384	62.5
PL07	20.625	52.384	62.5
PL08	22.5	52.384	62.5
PL09	16.875	50.479	62.5
PL10	18.75	50.479	62.5
PL11	20.625	50.479	62.5
PL12	22.5	50.479	62.5
Northern Germany:			
DE01	13.125	54.289	500.0
DE02	7.5	52.384	500.0
DE03	9.375	52.384	500.0
DE04	11.25	52.384	500.0
DE05	13.125	52.384	500.0
DE06	15	52.384	500.0
DE07	7.5	50.479	400.0
DE08	9.375	50.479	400.0
DE09	11.25	50.479	400.0
DE10	13.125	50.479	400.0
DE11	15	50.479	400.0
Holland:			
NL01	5.625	52.384	1000.0
NL02	3.75	52.384	1000.0
Belgium:			
BE01	5.625	50.479	300.0
BE02	3.75	50.479	300.0

Cross-correlation vs distance between grid points for single countries

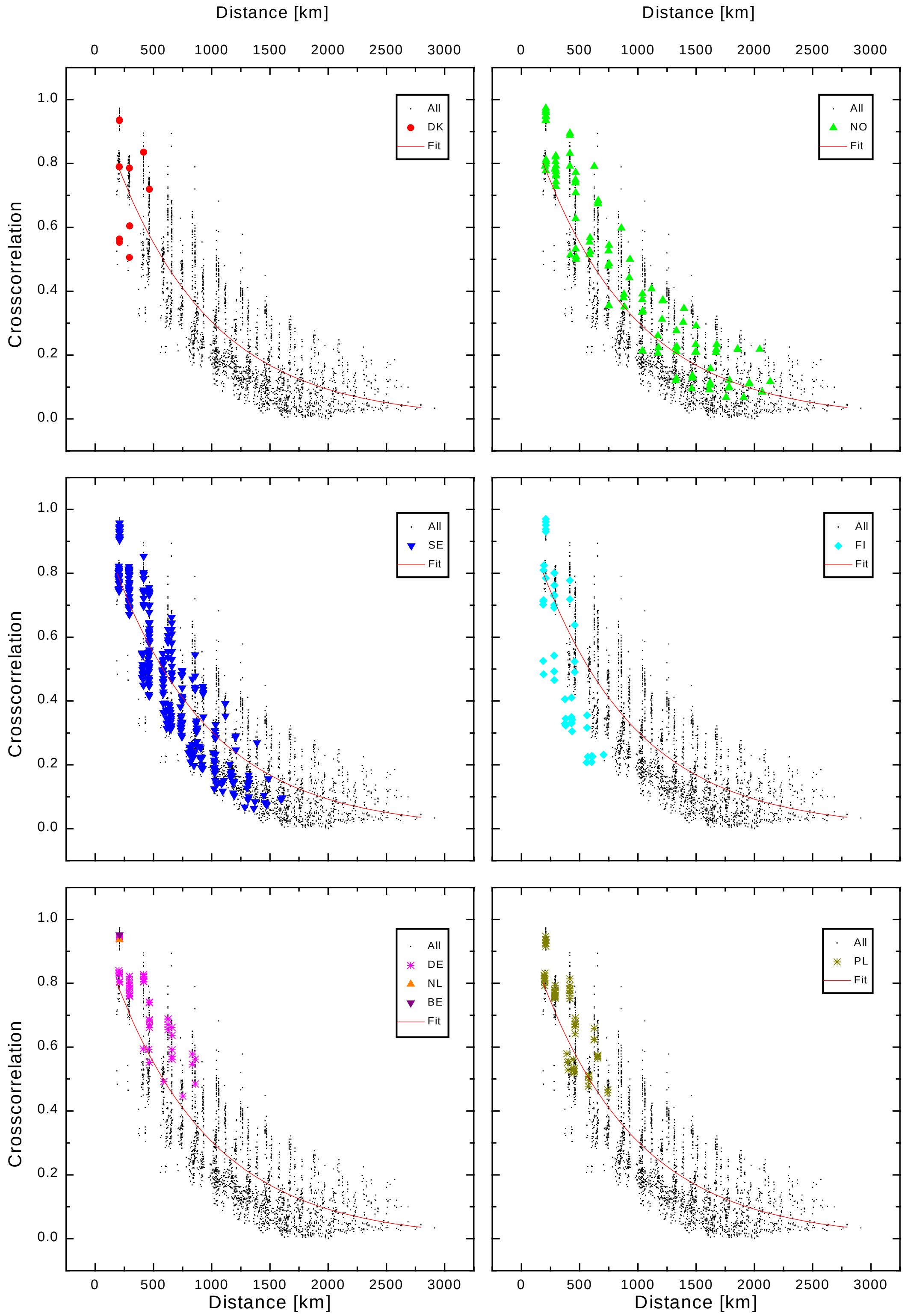

Figure 13: Cross-correlation vs distance between grid points. The full line is a fit of an exponential decay for all points. Analog to Figure 3.

Bibliographic Data Sheet **Risø-R-1182(EN)**

Title and authors

Equalising Effects of the Wind Energy Production in Northern Europe Determined from Reanalysis Data

Gregor Giebel

ISBN	ISSN
87-550-2698-2, 87-550-2754-7 (Internet)	0106-2840

Department or group	Date
VEA	May.2000

Groups own reg. number(s)	Project/contract No(s)
	1105-026-06

Pages	Tables	Illustrations	References
20	1	13	6

Abstract (max. 2000 characters)

The wind energy resource of Northern Europe is spread out over a geographically large area. This helps the utilities to integrate wind energy into their grids, since the generation is less variable, when it is combined from a larger area. The analysis was done based on 34 years of Reanalysis data. A short overview of the resource is given. The main analysis deals with the smoothing stemming from the averaging of multiple time series from many sites in the Nordic countries and south of the Baltic/North Sea.

Descriptors INIS/EDB

ELECTRIC UTILITIES; GEOGRAPHICAL VARIATIONS; INTERCONNECTED POWER SYSTEMS; POWER GENERATION; POWER TRANSMISSION; SCANDINAVIA; TIME-SERIES ANALYSIS; WIND;WIND POWER

Available on request from Information Service Department, Risø National Laboratory,
(Information Service Department, Risø National Laboratory), P.O.Box 49, DK-4000 Roskilde, Denmark.
Telephone +45 4677 4004, Telefax +45 4677 4013