High wind power penetration by the systematic use of smoothing effects within huge catchment areas shown in a European example

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ABSTRACT: Europe currently has by far the highest installed wind power capacity of all regions in the world. However, this is not due to Europe being the best possible place to build wind power, but rather to a favourable political climate. Owing to the rapidly increasing use of wind power, the aspect of integrating high levels of wind power into the grid is becoming more and more important. Because of the intermittent nature of wind, the quality of the electricity is affected by power fluctuations that can occur for short periods of time, such as a few seconds up to periods of a couple of months. The short term fluctuations even in small regions are significantly smoothed by increasing the number of turbines while long term variability decreases when the wind power is harvested from a large area. An area as big as Europe already shows good prospects for a smoothing of wind power output through the spatial distribution of generation. Furthermore there are areas surrounding Europe with high resources where harvesting of wind power could be economical, even including the costs of transport to Europe, using efficient transmission systems (such as High Voltage Direct Current HVDC) to harvest wind power for a European electricity supply. However, the variability significantly decreases when the wind power is harvested from such a large area. This paper presents analyses of power output data of individual wind turbines, wind farms, and clusters of wind farms on a wide range area up to some thousands of kilometres. With growing distances between wind farms a smoothing of the total power output occurs due to the lower correlation of wind speed. At high penetration this change of the temporal behaviour of the total wind power production significantly influences the backup systems necessary to provide a reliable electricity supply. By comparison of the electricity consumption and the available wind power the effect of spreading out wind energy generation to a large area is shown. Using only the existing storage capacity in Europe, a big proportion of the total electricity demand could be supplied by wind energy. The calculations are based on data from the German "250 Megawatt Wind" programme and from the European Centre for Medium-Range Weather Forecasts (ECMWF).

1 INTRODUCTION

The technical potential of wind energy in Europe is certainly ample to provide all local electricity needs. However, land based electricity production is limited by the relatively high population density and the corresponding intensive use of land. This leads to a significant reduction of usable land and thus of the wind energy potential which can be exploited. To reach high wind power integration it will be necessary to successively use worse sites where the annual production is lower. In the case of Germany the resulting mean value is estimated to be about 1600 Full Load Hours (**FLH**) [Q2000] - so that the costs of electricity will be relatively high. In Germany it is estimated that a maximum of about 17% of today’s electricity production could be gained from wind power. The situation is similar for other European countries. There are two possibilities to further enlarge the penetration wind energy. Where it is possible these countries could exploit the offshore potential or they could import wind power from other countries. Higher potentials of good wind sites exist e.g. in northern Norway or in the northern parts of the UK. Both countries have relatively high local demand and especially Norway with its storage hydropower based electricity system and its growing lack of electrical energy will therefore not really be forced to export wind energy for technical reasons [T1999]. The facts that both countries have very little wind power installed and so far have only small growth rates also are to be considered. Things change as soon as more distant regions are taken into account. There are huge areas with excellent wind conditions around Europe where the population densities are orders of magnitudes lower than in central Europe and where the same is true for today's electricity needs. To expand the use of wind energy to high proportions of the total electricity production sooner or later the electricity grid will have to be strengthened. This is true for consumption within most countries (see [T1999]) as well as considering the option of high electricity export rates. With growing distance the correlation of the wind speed significantly falls and the seasonal behaviour in some cases changes notably. Furthermore the quality of wind power prediction very clearly improves if it is harvested from larger catchment areas (see e.g. [F2000a])[1]. Therefore, the use of wind energy from distant regions could put us in a position to develop wind power to a major source of electricity production.

To shed some light on these roughly sketched ideas, different aspects of the systematic use of wind energy within huge catchment areas for a future electricity supply with high wind power proportions will be discussed in a European example.

2 SOURCE OF WIND DATA

For a detailed study of the possible role of wind energy in a future electricity supply within a very extended system, the interplay of the wind power production from all the different regions together is of crucial importance. The data used have to represent a realistic approximation of the spatio-temporal behaviour of wind. For many regions there are, if any, only very sparse and incomplete measurements available. As a result of the ECMWF Reanalysis project data are available which closely fulfil these needs. Most of the data used for the following analyses are taken from the ECMWF's ERA-15 Reanalysis project [EC1996]. The ERA-15 production system generated re-analyses from December 1978 to February 1994 with a 6-hour time step. The data are calculated in spectral T106 resolution - corresponding to a horizontal resolution of about 1.125 degrees - with 31 vertical levels. For this study the two of these levels close to 33m and 144m above ground were used to calculate the world-wide wind conditions at 80m hub height. The wind data were converted to power using the characteristics of a wind turbine (**WT**) with variable speed, 80m hub height 1.5 MW capacity and 66m rotor diameter.

For the correlation calculations we used data from the 250-MW Wind Program founded by the German Federal Ministry of Economics and Technology [I2000]. At 230 selected sites in Germany, data loggers and wind measurement equipment were installed to measure electrical power, wind speed, and wind direction at a 10 Hz sample rate. Usually 5 minute average data are stored in a data base but 10 Hz data are available for some sites as well.

[1] If e. g. catchment areas of a stretch of 100 km (60 mi) and 5000 km (3100 mi) are compared the prediction error may diminish by almost one order of magnitude [F2000b].

3 WIND ENERGY POTENTIAL

One result of the calculations is the potential annual production for Europe and its neighbourhood shown in **Figure 1**. In hilly regions such as the mountains close to Norway's coast line the results due to the spatial resolution of the ERA-15 model tend to be an underestimation of the actual conditions, whereas in more moderate terrain they seem to be relatively close to the real values. The technical potential of the whole area - only considering land sites with more than 1500 FLH - with 6 MW/km^2 (15.5 MW/mi^2) reaches close to 150.000 TWh and roughly equals 40 times today's consumption of the shown area. Hereby the mean production at all sites is about 2000 FLH.

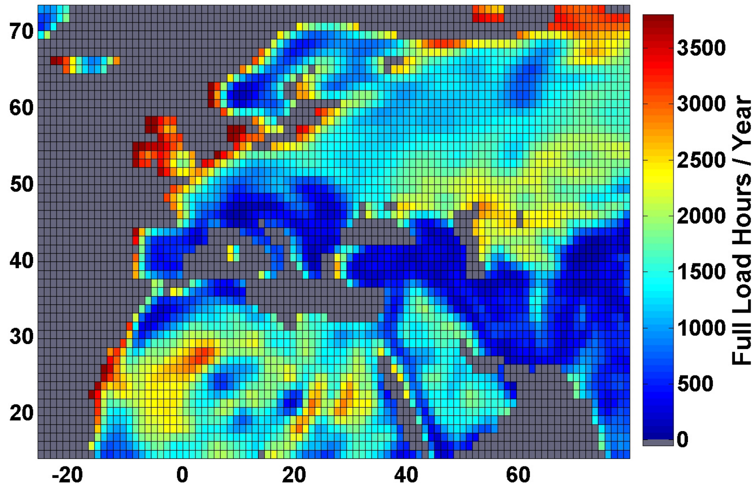

Figure 1 POSSIBLE ANNUAL WIND ENERGY PRODUCTION ON LAND SITES WITHIN EUROPE AND THE SURROUNDING COUNTRIES IN FULL LOAD HOURS PER YEAR OF VARIABLE SPEED WT WITH 80M HUB HEIGHT 1.5 MW CAPACITY AND 66M ROTOR DIAMETER. METEOROLOGICAL DATA 1979-1992 [EC1996].

4 SPATIO-TEMPORAL BEHAVIOUR OF WIND ENERGY

Because of the intermittent nature of wind, power fluctuations of wind farms occur for short periods of time, such as a few seconds or minutes, or periods of time a couple of hours. The smaller these fluctuations are, the easier they can be handled by other power plants to meet the demand. The fluctuations decrease with an increasing number of turbines, since their production is never entirely correlated.

4.1 Correlation of output power between single turbines, wind farms and distant areas

The short term variations are significantly smoothed even within a single wind farm. **Figure 2** shows the correlation coefficient of the power change (**ΔP**) of two wind turbines at a distance of 170 m (560 ft) for different averaging times. The calculation is based on 5 data sets with a few hours of length each. As expected, they are highly correlated at an averaging time above some minutes. Up to 1 minute, the correlation coefficient is below 0.2, which is mostly uncorrelated and means that even closely located wind turbines can obtain high benefits in terms of regulation burden. As soon as the power is produced in bigger wind farms with many wind turbines these short term fluctuations should be smoothed to negligible values and thus they will no longer have to be discussed in the following considerations.

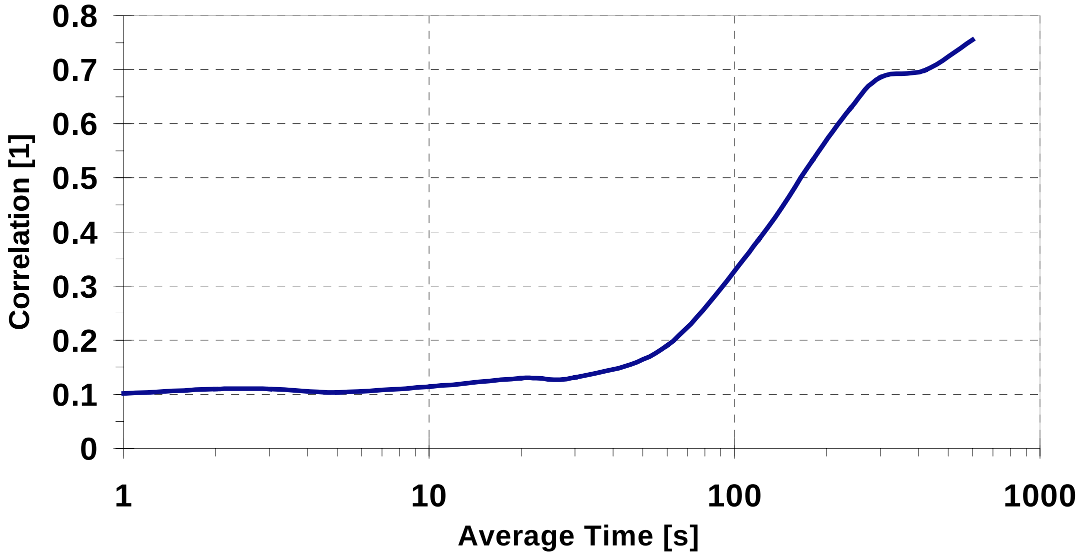

Figure 2 CORRELATION OF THE CHANGE OF WIND POWER (**ΔP**) OF TWO WIND TURBINES SPACED 170 M APART (CALCULATED FROM MEASURED 10 HZ DATA OF **WMEP**) VERSUS AVERAGING TIME.

By enlarging the distance between the wind farms even longer term fluctuations are reduced. **Figure 3** shows the mean correlations of wind power changes (**ΔP**) for longer averaging times and longer distances derived from measured **WMEP-**data of 176 turbines. The averaging time ranges from 5 minutes up to 12 hours. The correlation coefficients of the output from the wind turbines compared were classified according to the distances. The correlation coefficient for 5-minute data drops to almost zero after a few kilometers. The calculations using 30-second or 1-minute averages suggest that turbines located even closer would be uncorrelated. The result is a signifi-

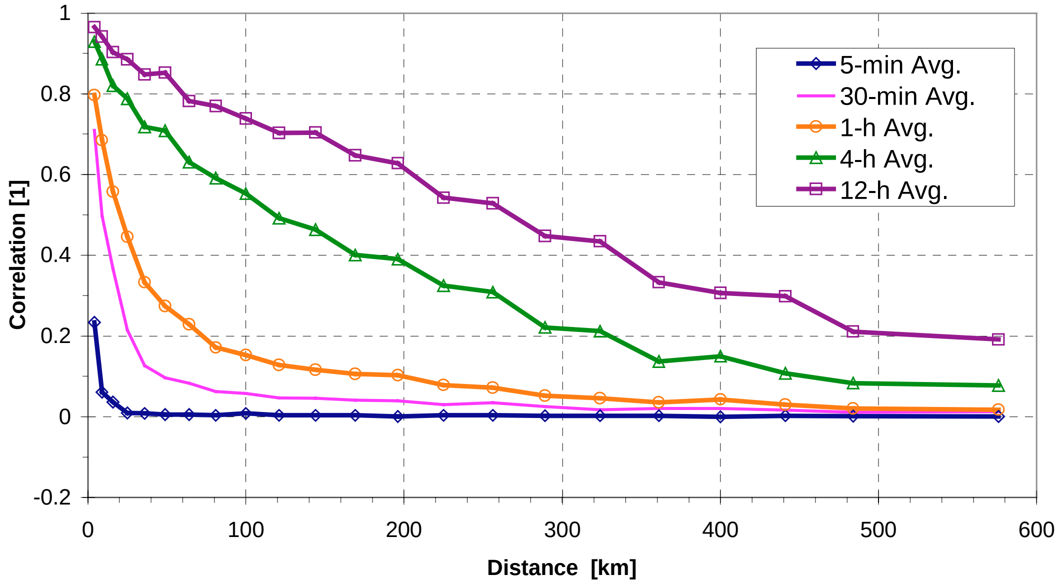

Figure 3: MEAN CORRELATION OF THE CHANGE OF WIND POWER (**ΔP**) VERSUS DISTANCE AT DIFFERENT AVERAGING TIME SPANS VERSUS DISTANCE DERIVED FROM MEASURED WMEP-DATA OF 176 TURBINES.

cant decrease in the system regulation burden with increasing number of wind turbines, even if the wind turbines are in close proximity.

The **ΔP-lines** in **Figure 4** show the same calculation for longer averaging time up to one month and the correlation of the monthly average absolute wind power (**P-dots**) derived from **ECMWF**-data. Each time series used stretches over one year and represents a set of **ECMWF** grid points within a bigger region[2] and thus a catchment area of up to some 100,000 km^2 (38,600 mi^2). Between 1500km (930 mi.) and 2000 km (1240 mi.) the mean correlation of **ΔP** almost drops down to zero and even becomes slightly negative for very long distances. The dots show the correlation not between the change in power but between the one month average of absolute

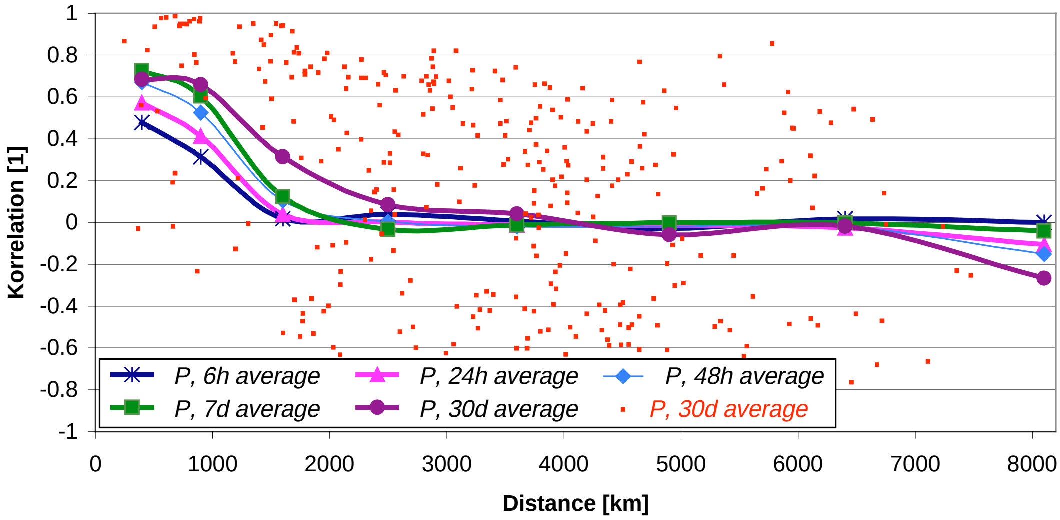

Figure 4: CORRELATION OF THE MONTHLY AVERAGE WIND POWER (**P-DOTS**) AND IT'S CHANGES (**ΔP-LINES**) WITHIN DIFFERENT AVERAGING TIME SPANS DERIVED FROM **ECMWF**-DATA VERSUS THE REGIONS DISTANCES.

power. Even at relatively short distances there are sites with a negative correlation of the monthly average. Combining these sites carefully could save a lot of storage needs.

5 Benefits of huge catchment areas for the electricity

Since, as shown, the temporal behaviour of wind power improves with the growing size of the catchment area used for its production, an example will be studied in more detail as the main topic of this chapter. Thus some favourable regions which are described in the following have been selected.

5.1 SELECTED REGIONS: INTRODUCTION

In addition to western European sites three regions in the European neighbourhood lie within the centre of the following considerations. (In what follows we assume the installation of wind

[2] In 19 of these bigger regions with good wind conditions around Europe there is at least one set with the best sites selected. If further good sites are available a set of second quality and where it's use seems to be reasonable a set of offshore grid points is added. Altogether this sums up to 43 separated sets of wind power data.

power at 2.4 MW/km^2 (6.2 MW/mi^2), which is rather conservative.) One is the **northern Russian and western Siberian region** **(Region a)** where the expected annual production at the selected sites lies between 3000 and 3400 averaging 3100 FLH. These numbers are consistent with the Russian Wind Atlas [S2000]. The total capacity that could be installed amounts to 350 GW and 1100 TWh annual electricity production. A second region **(Region b)** lies within **Kazakhstan** close to the Caspian Sea. Here the expected annual production at the selected sites lies between 2500 and 2800 averaging to 2600 FLH. Single measurements [B1987] confirm these expectations. Another study arrives at significantly higher velocities, from which 4000 FLH at selected sites can be derived [N1999]. The total capacity that could be installed amounts to 210 GW and 550 TWh annual electricity production. The third extra-European region is divided into two subregions within the western Sahara. The first **(Region c)** lies in **southern Morocco**. Here the expected annual production at the selected sites lies between 3200 and 3700 averaging 3400 FLH. Here single wind measurements come to significantly better results [E1999]. From these measurements at selected sites a annual production of more than 4500 FLH can be derived. In this Region 120 GW could be installed, leading to 400 TWh annual electricity production. The second subregion **(Region d)** lies in **Mauritania**. Here the expected annual production at the selected sites lies between 2650 (inland) and 3250 (closer to the coastline) averaging 3000 full load hours. The total installable capacity corresponds to 105 GW and 320 TWh annual electricity production.

For Europe itself **(Region E)** in this study a selection of better wind sites within the **EU and Norway** has been made. This selection would lead to a higher proportion of the total capacity in the more northern countries. E.g. 25% of the capacity are assumed in Ireland and Great Britain (In these two countries the total installable wind capacity might be higher. In order not to dominate the total production by the conditions of a relatively small area the capacity has been limited.). Overall the European capacity at the considered sites is assumed to be about 150 GW and 400 TWh annual electricity production. This amounts to 2700 FLH on average. These estimations take the population density into account, which in the western European countries roughly lies two orders of magnitude above the one in the other regions. Therefore the western European capacity lies far below the technical potential.

5.2 TOTAL CAPACITY WITHIN THE SELECTED REGIONS

The potentials described in the above section altogether make a capacity of nearly 950 GW and close to 2800 TWh annual electricity production. This is more than the total demand of the EU-countries plus Norway which was 2100 TWh in 1997. The average production exceeds 2900 full load hours.

5.3 TEMPORAL BEHAVIOR OF WIND POWER WITHIN THE SELECTED REGIONS

Since the total capacity of the selected favourable wind regions in comparison to the total demand is high, the temporal behaviour of the potential production becomes an important consideration. One of the questions of interest is how the seasonal production profile corresponds with the electricity demand. **Figure 5** shows the monthly mean production of the selected regions where the graphs **a)** to **d)** represent the Extraeuropean and **E)** the European production. Graph **G)** shows the monthly mean electricity consumption of EU-countries plus Norway. It represents 1930 TWh annual consumption, supplied by a rated power plant capacity of 465 GW. **F)** is a combination of the possible wind power production at all regions (**„Region“ F**). Here it is assumed that about one third of the capacity would be installed within the western European countries, while the remaining part of the rated power is distributed in equal shares over the other regions.

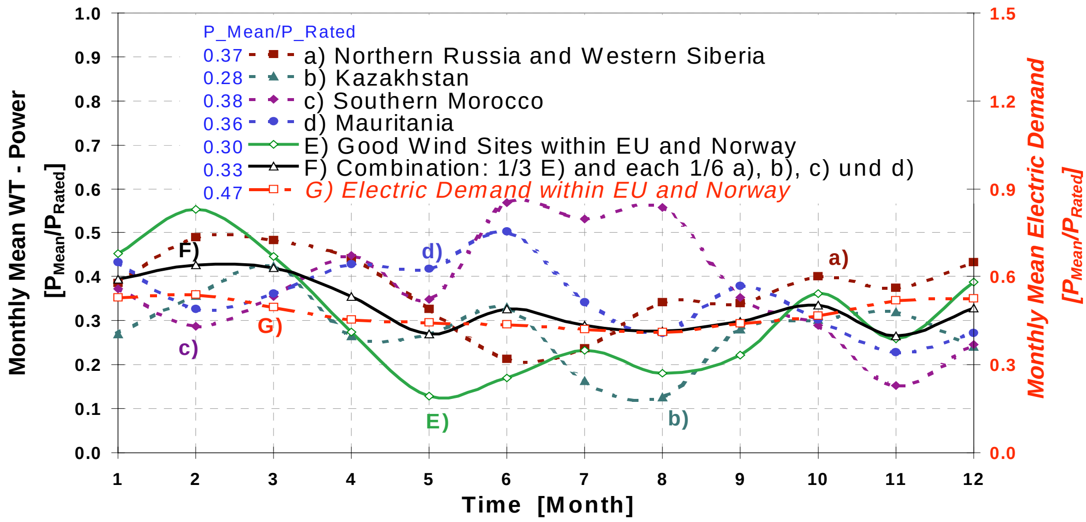

Figure 5 MONTHLY MEAN WIND POWER PRODUCTION OF SELECTED REGIONS: THE GRAPHS **A)** TO **D)** REPRESENT THE EXTRAEUROPEAN **E)** THE EUROPEAN PRODUCTION AND **F)** IS A COMBINATION OF WIND POWER AT ALL REGIONS. **G)** SHOWS THE ELECTRIC DEMAND WEIGHTED WITH THE TODAY'S RATED POWER OF ALL POWER PLANTS INSTALLED.

Europe as well as the northern Russian and western Siberian region and Kazakhstan are typical winter wind areas, whereas the Moroccan and Mauritanian regions are dominated by Passat winds and thus by summer wind maxima. The seasonal behaviour of the very simple configuration represented by graph F is much better suited to follow the demand curve than the European resources alone.

Another important question is how far it is possible to compensate local fluctuations of the wind power production with a shorter time span by engaging a large area for its production. The stochastic behaviour significantly changes with the size of the area. In **Table 1** the relative standard deviation of the wind power time series with different sizes of the used catchment area are listed. The standard deviation is divided by the mean production in each region. This is done for different time spans: 6 hourly (in the resolution of the wind data), weekly mean and monthly mean values.

Table 1: RELATIVE STANDARD DEVIATION OF THE WIND POWER TIME SERIES WITH DIFFERENT SIZES OF THE USED CATCHMENT AREA.

Region	DK-D*	E (Europe)	F (all regions)
6-hour time step	88%	59%	33%
weekly mean	64%	49%	22%
monthly mean	46%	41%	16%

* The region DK-D is the potential common production area of Denmark and Germany with relatively small size.

In general the fluctuations rapidly decline with the growing size of the catchment area (see also [G2000]). For the simultaneous use of all regions mentioned the relative standard deviations are for all averaging times close to 30% of those within the area DK-D. The production is much smoother and the need of fast reactions to changes as well as of storage systems is significantly lower.

This change can also be seen if one considers the maximum and minimum power production within the system. In **Table 2** among other figures the occurring extremes can be found. Considering the results shown it is obvious that the use of a larger area is superior in all aspects to a system of smaller scale.

Table 2: SOME STATISTICAL FIGURES OF WIND POWER TIME SERIES WITH DIFFERENT SIZES OF THE USED CATCHMENT AREA.

Region	**DK-D***	**E (Europe)**	**F (all regions)**
I extremes of actual wind power			
max	100%	80%	67%
min	0%	3%	4%
II frequency of occurrence of extremes of wind power			
over 60%	18%	8%	1%
under 20%	46%	37%	10%
III lack (-) or excess (+) of wind power production (**WPP**) weighted with all WPP within the used area			
over 60%	+11%	+2%	+0.1%
under 20%	-18%	-8%	-1%
under 30%	-34%	-24%	-9%
IV total share of the production while actual power is			
over 60%	46%	18%	2%
under 20%	11%	16%	5%

*s. **Table 1**

The combined trans-European use F includes both Intra- as well as extra-European wind power production. Within this system times with very low or high production become relatively rare incidents. (If furthermore offshore wind energy was used the low end could be considerably higher [C1999]). The system could provide 30% of base load if a backup system with 26% of the rated power of the installed WTs was engaged. This backup would therefore on average only be working to 11% of its capacity.[3] Thus it would be best to use power plants that require low investment. The total investment for modern gas turbines as backup e.g. could lie far below 10% of the investment in the wind power capacity and therefore only slightly change the production costs.

6 BACKUP, STORAGES AND TRANSPORT CAPACIY

At this point the authors would like to permit themselves some strategic considerations. If the trans-European wind energy F was used in accordance with the explanation in **Chapter 5.2** the maximum capacity would be about 460 GW. In the following the resulting time series of wind power production is compared to the approximated time series of the consumption **G**. The second idea considered in the following is that with the same temporal behaviour of the wind energy production roughly the equivalent of the consumption could be produced. This would require enlarging the rated wind power to 660 GW. **Table 3** shows some results of these considerations. The surplus energy production is relatively low in both cases. In the 660 GW case it is almost as high as the cumulated power deficit. This would mean that most of the electricity production could come from wind energy if there were enough active storages such as pump storages available.

[3] These 11% stem from multiplying the lack of energy (**Table 2**; section III; line „under 30%“; column F) with the mean production F (see **Figure** graph F) divided by the difference between the required base load of 30% and the minimum wind power (**Table 2**; section I; line „min“; column F). So 11% ≈ |(-9%*33%)/(30% - 4%)|.

Table 3: RESULTS OF A VERY HIGH WIND POWER PENETRATION CASE STUDY. CATCHMENT AREA **F** AND CONSUMPTION **G**.

Rated Wind capacity*	460 GW	660 GW
Maximum power surplus	76 GW	208 GW
Maximum power deficit	237 GW	216 GW
Sum of power surplus *	1%	13%
Sum of power deficit *	32%	14%
Total wind power production *	69%	100%

* rated by consumption

Today's total storage capacity of storage hydropower plants within the considered supply area lies at roughly 10% of the consumption in the area. Their annual production is in the range of 15% (the main part within Scandinavia) and thus higher than the required 14%. However, the installed capacity of these power plants is not sufficient with 95 GW to solve all deficit situations. Enlarging the rated power at the storage stations might be an appropriate way to overcome this problem.

The good regions for wind power production as well as the existing storage systems are spread over great distances. The huge amounts of electricity that would have to be transported would require much higher net capacities than available today. To avoid unacceptably high losses High Voltage DC technique could be engaged. With existing technology the losses at full load could e.g. be as low as 16% per 4000 km (2480 mi) [H1999].

Calculating with 1000 €/kW rated WT-capacity, 5% real interest rate, 20 years lifetime, 2% of the total investment as annual O&M costs and with the mean production corresponding to „Region“ **F** the wind power at production site would cost 3.5 €c/kWh. For the mean southern Moroccan site **c** they would be a little lower at 3 €c/kWh. The transport over 4400 km (2730 mi) which could e.g. deliver the power to Kassel (Germany) would lead to mean losses of 10% if done with a HVDC line of about 5 GW capacity [C2000]. The rated wind power is assumed to be the same as the line capacity. In this example the annuity of the HVDC line would add 33% to the total annual costs of the installed WTs. At the end of the HVDC line the costs would be 4.5 €c/kWh. For the best wind sites within the regions even better results are found.

7 SUMMARY AND CONCLUSION

The integratability of wind power into the European grid increases with increasing size of the catchment area. While already the distribution of wind energy generation over all of Europe would be beneficial for the reliability of the supply, the use of extra-European sites with their extraordinary wind speeds could be advantageous, in terms of economics and reliability. In this paper, we could show that spreading out wind energy generation to different large areas with very good wind resources outside of Europe decreases the variability of the generation and thereby the need for back-up or storage power plants. With the existing storage capacity of Europe, a large proportion of the total electricity demand could be served by wind energy. Using HVDC for the transport, the resulting electricity would still be economically viable. For the Moroccan example, costs of 4.5 €c/kWh (in Kassel) are estimated. Building wind farms on a large scale in the areas analysed would also constitute a win-win situation for all countries involved. Some of Europe's neighbours seem to be the first to be faced with economic and ecological damage through the climate change (especially lack of precipitation). But there is also the very interesting chance to combine renewable energy production with development aid. Therefore let's do a short calculation with Morocco and Germany as an example. Germany spends 40 Billion Euro annually on its electricity supply which is about 2% of its GDP, whereas the total GDP of Morocco lies somewhat above 30 Billion Euro. Today's Moroccan electricity consumption is 2.5% of Germany's 490 TWh. Let us assume Morocco would produce 10% of the European demand (G). This would involve a total investment of 57 Billion Euro for the WTs which would be erected in Morocco and is close to twice its GDP. The transfer would probably extend over several decades. To follow such a concept would among other things mean developing the infrastructure and thus could become a form of development aid worthy of the name, based on the needs of both sides.

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