A Comparison of Intra- and Extraeuropean Options for an Energy Supply with Wind Power

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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. There are areas with high resources around Europe where harvesting of wind power could be economical, even including the costs of transport to Europe. One problem to be overcome is that wind energy by nature is a variable resource and cannot be scheduled like conventional power plants. However, the variability significantly decreases when the wind power is harvested from a large area. Already Europe itself shows big prospects for a smoothing of wind power output trough the distribution of generation. Using efficient transmission systems (such as High Voltage Direct Current **HVDC**) to harvest wind power from areas outside Europe that have a very good wind resource is a viable option, even for large scale transfers of energy. This paper is to shed some light on the wind energy potentials in and around Europe, and the smoothing effects occurring due to the low correlation of wind farm output with distances of thousands of kilometres in between.
Keywords: Large Scale Integration, Recourses, National/International, Energy Policies, Dispersed Turbine Systems

1 INTRODUCTION

The technical potential of wind energy in Europe is big enough by far 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. In the case of Germany this leads to a significant reduction of usable land and thus of the wind energy potential which is estimated to be in the range of 15 GW or about 24 TWh per year [1]. This roughly amounts to 5% of Germanys today's consumption. To reach this goal it will be necessary to successively use worse sites where the specific production is lower. In the case of Germany the resulting mean value is estimated to be about 1600 Full Load Hours (**FLH**) - so that the costs of electricity will be relatively high. On the other hand, the total capacity would - if the yearly installation rate remains stable - be reached within the year 2006. This would be a notable deadline for the wind industry. The situation is similar for other European countries. There are two possibilities to further enlarge their wind energy share. Where possible these countries could exploit the offshore potential or they could import wind power from other countries. Higher potentials of good wind sites exist eg 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 [2]. 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 lie 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 shares 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 [2]) 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 is changing notably. 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, in the following different aspects of intra- and extraeuropean options for an energy supply with wind power will be discussed.

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. In 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 [3]. The ERA-15 production system generated re-analyses from December

1978 to February 1994 with a 6-hour timestep. 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 modern wind turbine (**WT**) with variable speed, 80m hub height 1.5 MW capacity and 66m rotor diameter.

3 WIND ENERGY POTENTIAL

One result of the calculations is the potential yearly production for Europe and its neighbourhood shown in **Figure 1**.

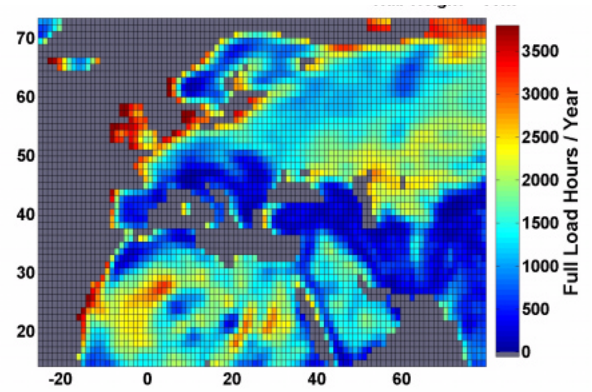

Figure 1 Possible annual wind energy production on land sites within Europe and its surrounding in full load hours of variable speed WT with 80m hub height 1.5 MW capacity and 66m rotor diameter. Meteorological data 1979-1992 [3].

In hilly regions such as the mountains close to Norway's cost 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 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.

3.1 SELECTED REGIONS

In addition to western European sites three regions in the European neighbourhood lie within the centre of the following considerations. Following we assume the installation of wind power at 2.4 MW/km^2, which is rather conservative.

One is the **northern Russian and western Siberian region** (**Region a**) where the expected yearly production at the selected sites lies between 3000 and 3400 averaging to 3100 FLH. These numbers are consistent with the Russian Wind Atlas [4]. The total capacity that could be installed amounts to 350 GW and 1100 TWh yearly electricity production. A second region (**Region b**) lies within **Kazakhstan** close to the Caspian Sea. Here the expected yearly production at the selected sites lies between 2500 and 2800 averaging to 2600 FLH. Single measurements [5] confirm these expectations. Another study arrives at significantly higher velocities, from which 4000 FLH at selected sites can be derived [6]. The total capacity that could be installed amounts to 210 GW and 550 TWh yearly electricity production. The third extraeuropean region is divided into two subregions within the western Sahara. The first (**Region c**) lies in **southern Morocco**. Here the expected yearly production at the selected sites lies between 3200 and 3700 averaging to 3400 FLH. Single wind measurements come here to significantly better results [7]. From these at selected sites a yearly production of more than 4500 FLH can be derived. In this Region 120 GW could be installed, leading to 400 TWh yearly electricity production. The second subregion (**Region d**) lies in **Mauritania**. Here the expected yearly production at the selected sites lies between 2650 (inland) and 3250 (closer to the coastline) averaging to 3000 full load hours. The total installable capacity corresponds to 105 GW and 320 TWh yearly electricity production.

For Europe itself (**Region E**) in this study a selection of better wind sites within the **EU and Norway** is made. This selection would lead to a higher proportion of the total capacity in the more northern countries. Eg 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 yearly electricity production. This amounts to 2700 FLH on average. These estimations take the population density into account and therefore lie far below the technical potential.

3.2 TOTAL SELECTED CAPACITY

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

4 SPATIO-TEMPORAL BEHAVIOUR OF WIND ENERGY

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 point of view. One of the questions of interest is how the seasonal production profile corresponds with the electricity demand. **Figure 2** 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 yearly consumption, delivered 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.

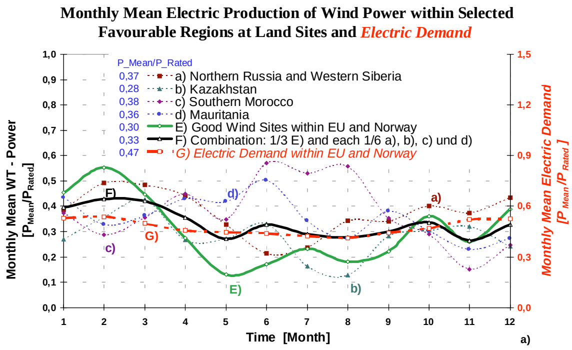

Figure 2 Monthly mean wind power production of selected regions: The graphs a to d represent the Extraeuropean E the European production and F a combination of wind power at all regions. G shows the electric demand weighted with the today's rated power of all power plants installed.

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 monthly 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 size of the catchment area (see also [8]). 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. Viewing 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 Transeuropean use F realises both Intra- as well as Extraeuropean 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 [9]). The system could provide 30% of base load if there was engaged a backup system with 26% of the rated power of the installed WTs. This backup would therefore on average only be working to 11% of its capacity.[1] Thus it would be best to use power plants that require low investment. The total investment for modern gas turbines as backup eg could lie far below 10% of the investment in the wind power capacity and therefore only slightly change the production costs.

5 BACKUP, STORAGES AND TRANSPORT CAPACIY

At this point the authors would like to permit themselves some strategic considerations. If the Transeuropean wind energy F was used in accordance with the explanation in **chapter 3** the maximum capacity is 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 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

[1] These 11% are stem from multiplying the lack of energy (Table 1; section III; line „under 30%"; column F) with the mean production F (see Figure 2 graph F) divided by the difference between the required base load of 30% and the minimum wind power ((Table 1; section I; line „min"; column F). So 11% ≈ |(-9%*33%)/(30%-4%)|.

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.

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 yearly 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 with 95 GW not sufficient 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 far 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 be 16% per 4000 km [10].

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 which could deliver the power to Kassel (Germany) would lead to mean losses of 10% if done with a HVDC line of about 5 GW capacity [11]. The rated wind power is assumed to be the same. 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.

6 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 extraeuropean sites of extraordinary wind speeds could be economically and reliabilitywise advantageous. In this paper, we could show that spreading out wind energy generation to four large areas outside of Europe with very good wind resources 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 big 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 at the assumed feed-in point in Kassel. For the Moroccan example, costs of 4.5 •c/kWh 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 the European neighbours seem to be the first to be faced with economic and ecological damage by the climate change (especially lack of precipitation). But there is also the very interesting possibility to combine renewable energy production with development aid. Therefore let us do a short calculation with Morocco and Germany as example. Germany yearly spends 40 Billion Euro for 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 financial and know-how transfer would probably stretch out over the next decades. To follow such a concept would among other implications mean developing the infrastructure and thus could become a form of development aid worthy of this name based on the needs of both sides.

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