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Characterization of the wind power resource in Europe and its intermittency

Alexandra Cosseron [a,]*, Udaya Bhaskar Gunturu[b], C. Adam Schlosser[b]

[a]*Ecole Polytechnique, Route de Saclay, 91120 Palaiseau, France*
[b]*MIT Joint Program on the Science and Policy of Global Change,*
77 Massachusetts Avenue, 54-1318, Cambridge MA 02139-4307, USA

Abstract

Wind power is assessed over Europe, with a special care given to the quantification of intermittency. Using the methodology developed in Gunturu and Schlosser [1], the MERRA boundary flux data was used to compute wind power density profiles over Europe. Besides of the analysis of capacity factor, other metrics have been designed to further quantify the availability and reliability of this resource and the extent to which wind-power intermittency is coincident across Europe. The presented analysis leads to the conclusion that wind-proponents' favourite statement, "wind always blows somewhere", may not be so true.

Keywords: Wind power density; clean energy; capacity factor; intermittency; coincidence.

1. Introduction

During the past few years, a renewed interest in wind energy and thus in the assessment of wind power resource have been witnessed. Indeed, wind power resource is a renewable energy resource for which the technology is among the most mature and the production of electricity is clean. Most recently, the Fukushima catastrophe in May 2011 has brought about a revival of assessing large-scale deployments of clean, renewable technologies. Many European countries have put a strong stress on their will to phase

* Corresponding author. Tel.: +33-614-342-653.
E-mail address: alexandra.cosseron@polytechnique.org.

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out nuclear power generation to move heavily towards renewables. Thus, the present geopolitical situation in Europe has never been so favorable towards renewables. Germany has clearly stated its will to go green. It was soon followed by Switzerland. Finally, the French government has stated its will to reduce the nuclear share in the French energy mix, from 75% to 50% in the French electricity production by 2025. As renewable share into European energy mix is progressively growing, a deep understanding of wind power availability and intermittency is required to prevent this renewable energy from becoming a threat to the grid stability. Given this, the presented analyses follow that of Gunturu and Schlosser [1], the goal is to replicate over Europe the wind-power density (WPD) potential (as was done over the United States). In this way, this work highlights capacity factor mapping, as well as wind-power intermittency and variability, which factors critically in the overall assessment and insights of wind power as a viable energy resource.

The data required for this study - air density, displacement height, friction velocity and roughness length - has been taken from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) database. MERRA is a reconstruction of the atmospheric state by assimilating observational data from different platforms into a global model using the GEO-5 Atmospheric Data Assimilation System (ADAS), Rienecker et al. [2]. The data assimilation included conventional data from surface-based, remote sensing platforms as well as data from several trains of satellites. The data set has a time resolution of an hour, averaged in time over each hour. Thus, as jumps in intensity within one hour are averaged, variability on time scales below one hour cannot be studied with this data set. Moreover, the data spans the time from 12:30 AM on 1st January, 1979 to 11:30 PM on 31st December, 2009. As a result, the data set provides an opportunity to look at the variation of the winds over several scales up to the decade scale. The domain considered for the study scans Europe from 34ºN to 71º30'N latitudes and from 26ºE to 42ºW longitudes. It spreads from Iceland to the western end of Ukraine and the resolution of the grid is 1/2°x1/3°.

2. Capacity Factor Analysis

2.1. Highlights of Capacity Factor computations

The capacity factor is defined as the fraction of the rated power (or maximum capacity) actually produced in a year. Given the exceptional length of the database used here, we extend this definition to be the rated power actually produced on an hourly basis over 30 years, from 1979 to 2009.

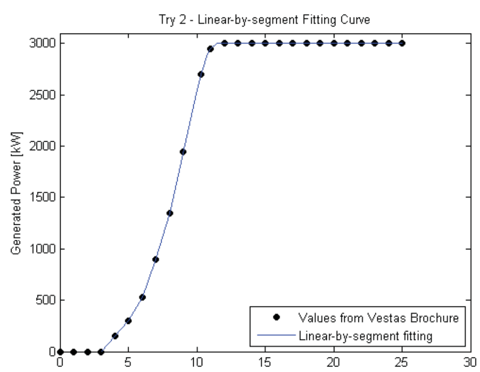

Fig. 1. Linear-by-segments fitting of IEC S model, from Vestas [5]

A study about the power harvested implies the choice of a referenced wind turbine to undergo computations. According to Efiong and Crispin [3] and the European Wind Energy Association (EWEA) [4], Vestas has long been the world's leading supplier of wind turbines. Moreover, their latest wind turbine is said to suit to the all range of wind-classes and exists in onshore and offshore versions. All of these considerations made the Vestas V112-3.0MW wind turbine particularly suitable for this study as our representative turbine.

As for its main characteristics, this turbine reaches 84 meters height; its blades have a length of 54.65 meters that leads to a rotor diameter of 112 meters. The maximal power generated is 3.0 MW (for the IEC S model chosen here). These characteristics are the same for the offshore model, expect for the hub height specified as being "site specific" by the manufacturer. Figure 1 presents the fitting used for the capacity factor computations, in which, for each wind speed in the different locations, was attributed a capacity produced, accordingly to the Vestas power curve [5].

2.2. First Results

Figure 2 displays the mean and median capacity factor (CF) over the thirty years of the MERRA database. As done in Bhaskar and Schlosser [1], the wind speed used to compute this capacity factor is the wind speed estimated at 80 m height, slightly below the hub height of the Vestas wind turbine used is 84 meters. According to the results displayed on Figure 2(a), Iceland, Ireland, United Kingdom and Denmark have the highest onshore capacity factor mean values, from 0.4 to 0.5. The second best onshore areas are the "Aeolus crescent", which spreads from northwestern France to western Ukraine and over the Kjolen Mountains with mean values ranging from 0.2 to 0.4. As for offshore regions, the best accessible spots remain along the Atlantic coasts, from western France to Estonia with mean values up to 0.6. The potential over Mediterranean and Black Seas is lower with its maximal mean values up to, respectively, 0.5 and 0.4.

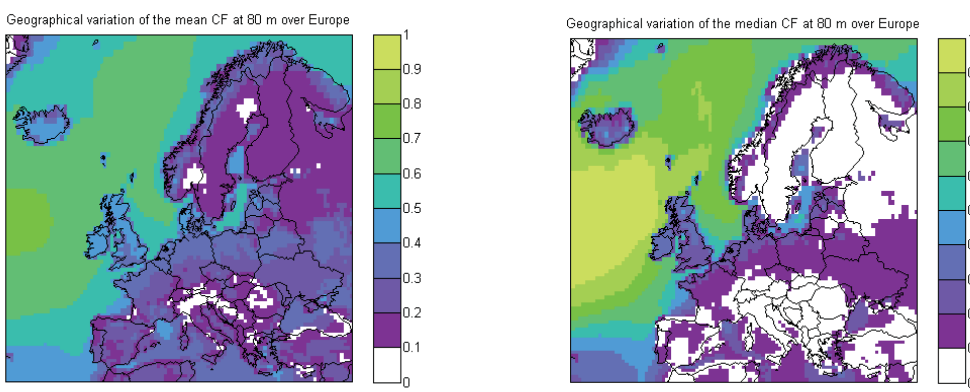

Fig. 2. Geographical variations of the (a) mean and (b) median capacity factor at 80 m over Europe.

Given the inherent skewness in wind speed frequency distribution, the behavior of the median values, shown on Figure 2(b), seems somewhat counter-intuitive compared to mean values. Indeed, while inland, Mediterranean and Black seas median values are approximately equal to half of the mean values, Atlantic offshore median values increase compared to mean values. However, this is consistent with the higher steadiness of offshore winds; in other words, this is consistent with the fact that offshore winds blow more regularly and with higher intensity than onshore winds, due to low roughness over widely open oceans.

3. Study of some unconventional parameters

One of the most important assumptions in aggregation of geographically dispersed wind turbines to mitigate intermittency is that wind at least blows at one of the two connected sites. This refers to the famous wind-proponent statement that contends that "wind always blows somewhere", as emphasized by Kiss and Janosi [6]. This assertion can be tested through new parameters, anticoincidence and null-anticoincidence, which constructions are detailed in Appendix B.

3.1. Anticoincidence Analysis

The idea is to assess, for each grid point of the area under consideration, if its surroundings points have wind when the central one has or has not. Instances of anti-correlation in wind-power states are counted and if this count is at least 50% of the total length of the time series, the two points are said to be anticoincident. Intuitively, if they are anticoincident for more than 50% of the time, the two sites can benefit, more often than not, from an interconnection. The term "anti-coincidence" is adopted here, as the metric is not a strict, statistical correlation, but rather an assessment of opposite wind-power state between any two points of interest.

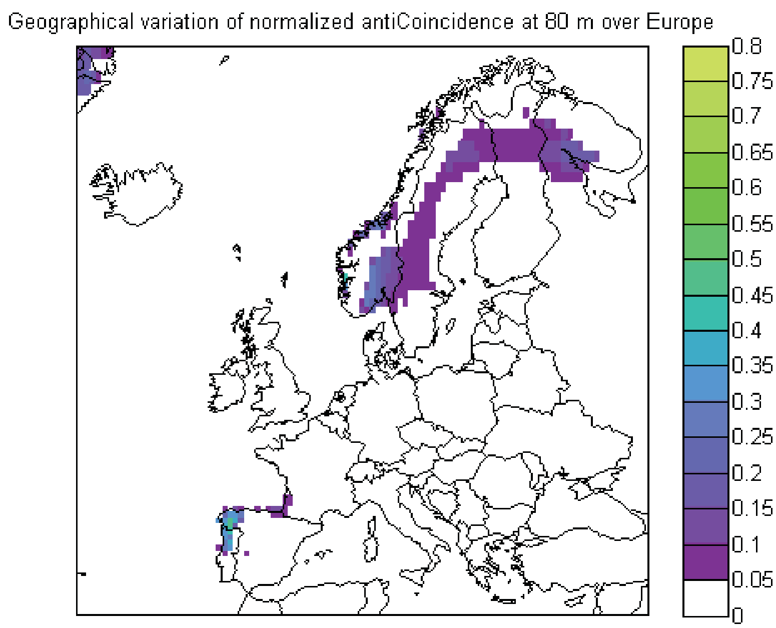

Fig. 3. Geographical variation of normalized anticoincidence of WPD at 80m height over Europe

Figure 3 shows the geographical variation of normalized anticoincidence of WPD at 80 m height over Europe. The color of each grid point shows the number of anticoincident points in a box of approximately 1000km×1000km around it, divided by the total number of points in the box. The white region shows complete lack of anticoincidence and thus, complete coincidence of intermittency. Thus, the points that have greater concentration of anticoincident points around them would presumably benefit more strongly from interconnection. Only the center of Scandinavian Peninsula, southwestern France, northwestern Spain and northern Portugal shows some fraction of anticoincident points. In addition, these values remain quite low for Scandinavian Peninsula and France, contrary to Spain and Portugal where some points have nearly half of the grid points in a region of approximately 1000km×1000km around them that are anticoincident.

Contrary to the United-States case studied by Gunturu and Schlosser [1], the widespread lack of anticoincidence cannot be explained by uniform low surface roughness associated with even terrain. This is evidenced by the presence of highly mountainous areas across the region of very low anticoincidence, mainly the Spanish Meseta, the Pyrenees, the Alps, the Balkan Dinaric Alps and the Kjolen Mountains.

3.2. Null-anticoincidence Analysis

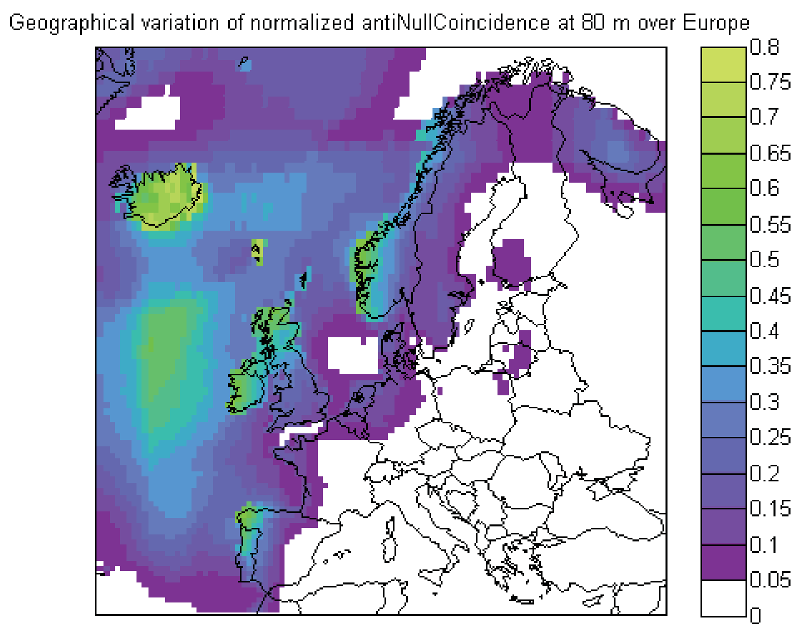

Fig. 4. Geographical variation of normalized null-anticoincidence of WPD at 80m height over Europe

Driven by the low level of anticoincidence across Europe, a relaxed criterion was investigated: null-anticoincidence. This time, opposite wind-power state with its surroundings of a grid point is assessed only when this grid point is in a non-windy state (for detailed definitions, see Appendix B); and, two points are termed "null-anticoincident" if the number of such instances is at least 50% of the number of the instances of the center not having wind (instead of 50% compared to the total length of the timespan as previously). The geographical variation of normalized null-anticoincidence of WPD at 80 m height over Europe is shown on Figure 4. Similarly to Figure 3, the color of each grid point shows the number of null-anticoincident points in a box of approximately 1000km×1000km around it, divided by the total number of points in the box. The white regions show complete lack of null-anticoincidence.

This figure shows very significant null-anticoincidence in Iceland, Norway, Scotland, Ireland and Northwestern Spain where the fraction of null-anticoincidence closest neighbor points reaches 0.7 and 0.8 levels. This means that, if there is no sufficient wind at one of these points, there are many sites around the point that have sufficient wind and interconnecting these sites can provide a steady wind power. It is also interesting to note that in the case of anticoincidence, the offshore regions do not have sufficient anticoincidence, whereas they satisfy the relaxed null-anticoincidence. In addition, the most significant lack of null-anticoincidence occurs in the eastern and southeastern parts of Europe.

Apart from the perspective of interconnecting to mitigate the intermittency in wind resource, this result has another significant consequence that due to the high coincidence, the intermittency in the eastern and southeastern parts of Europe is highly synchronized. Thus, if these regions are interconnected, then the synchronized high wind instances may result in very large wind power in the grid and the synchronized low wind situations will result in very low wind power output.

5. Conclusion

There are several studies that have looked at intermittency in a smaller scale - millisecond, second and minutes, for example, Makarov et al. [7], Parsons et al. [8], Smith et al. [9]. They pointed out that sudden rise or fall of wind power does not occur and fall in wind power at a site is gradual. Nevertheless, the impact of intermittency at the scales of an hour and longer is different. If the aggregated power from interconnected turbines falls on the scale of hours, the grid can be driven into heavy reliance of backup generation. Thus, interconnected wind farms must be chosen carefully otherwise it may threaten the stability of the grid and the security of energy supply. The present study allows some conclusions about the characteristics of wind power resource over Europe to be drawn. The capacity factor study provides highlights about availability of this resource. Further, the study of anticoincidence and null-anticoincidence variables allow a first assessment of the extent to which wind power can be employed as a base-load energy resource.

The limitations of the present study must be kept in mind. To begin with, the data used for construction of the wind resource is a result of the assimilation of measurements and satellite remote sensed data into a global model. Thus the imperfections of the model and the assimilation schemes are bound to influence the computed output. Further, the spatial resolution of the data might prevent this study to capture local effects. Indeed, very local topographic features that change wind speeds like mountain passes and valleys are ill-represented in this study. Furthermore, since the time resolution is an hour, intermittency and other phenomena of longer timescales and their effects can only be studied.

Nevertheless, some relevant tendencies can be drawn from this study: wind episodes across Europe can be highly coincident. While benefits of aggregation is seen for near-shore deployment, as reflected by higher null-anticoincidence of WPD, much of the onshore locations would need to rely on back-up generation technologies to prevent the European grid from major failure under a high wind power penetration into the energy mix.

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Appendix A. Wind computations

The similarity theory in boundary layer dynamics is employed to compute wind speed and wind power density. To estimate the mean wind speed, V_z, as a function of height, z, above the ground, the following variables are relevant: surface stress (represented by the friction velocity, u_*, and surface roughness (represented by the aerodynamic roughness length, z_0). The friction velocity, u_*, is defined as follows:

$$u_* = \left[\left(u'w'_s \right)^2 + \left(v'w'_s \right)^2 \right]^{1/2} \tag{1}$$

where u, v and w stand respectively for eastward, northward and upward moving Cartesian wind components, thus $u'w'_s$ and $v'w'_s$ respectively stand for kinematic flux of U and V-momentum in the vertical, and finally, the index s indicates that momenta are considered near the surface. The aerodynamic roughness length, z_0, is defined as the height where the wind speed becomes zero.

Moreover, over land, if the individual roughness elements are packed very closely together, then the top of those elements begins to act like a displaced surface. It can be defined a displacement distance, d , and a roughness length, z_0 , such as:

$$V_z = \left(\frac{u_*}{k}\right)\log\left[\frac{(z-d)}{z_0}\right] \tag{2}$$

for statically neutral conditions, where V_z is defined to be zero at $z = d + z_0$. It can also be added a function φ that depends on the stability of the boundary layer such as V_z could be expressed as:

$$V_z = \left(\frac{u_*}{k}\right)\log\left[\frac{(z-d)}{z_0} - \varphi\right] \tag{3}$$

For this study, the boundary layer is assumed to be neutrally stable, avoiding thus the additional φ function. As a result, Equation (2) only is used to compute wind speed at different heights. All the previous considerations come from Stull [10].

Furthermore, during the 1990s the general wind turbine height was 50 m. With the advancement of technology, the hub height of the turbine could be raised to 80 m, 100m and 120m and turbines of 80m hub height are the most common now. Thus, the estimation of wind resource and its variability at these different heights is imperative to study the behavior of wind power over Europe.
Then, to compute the wind power density at different heights, it is assumed that the air density does not differ appreciably at these heights through the well-mixed boundary layer. Thus, using the air density at the center of the lowest model layer ρ and the wind speed computed using the logarithmic wind profile above, the wind power density at these heights is estimated with the following equation:

$$P_z = \frac{1}{2}\rho V_z^3 \tag{4}$$

Hence, these estimates take into account the effects of surface heat flux on the friction velocity, the time variation in displacement height and roughness length.

Appendix B. Construction of the two unconventional parameters

The minimum wind power density (WPD) required for utility-scale power generation is 220 W/m^2 , according to Gustavson [11].To account for advances in technology, minimum wind power density for usable power generation is assumed to be 200 W/m^2 . Based on this assumption, the time series of wind power density at each grid point is converted into a binary sequence of 1s and 0s depending on if the wind power density is greater or less than 200 W/m^2 . 1s correspond to a windy state reported as W in Figure 5 while 0s correspond to a non-windy state reported as N.

To understand the spatial and temporal relationship between the wind resources at these grid points, the binary time series of windy and non-windy states are compared within a 19×19 grid point box, drawn around each grid point as shown on Figure 5. Given the 1/2°x1/3° resolution of the MERRA grids, the effective size of the box is approximately 1000 km×1000 km.

The binary times series of the wind-power state at R is compared to the one at every point, P, within this subdomain (Figure 5). The total number of time steps when R and P are in opposite wind-power states is then analyzed. If this count is at least 50% of the total length of the timespan, the two points are said to be anticoincident. The number of anticoincident points in the box around R is finally logged as the score of the point R, then the center of the box is moved to another grid point and the score of that point is determined. Thus, every grid point is evaluated and its score for the assumed criterion is determined.

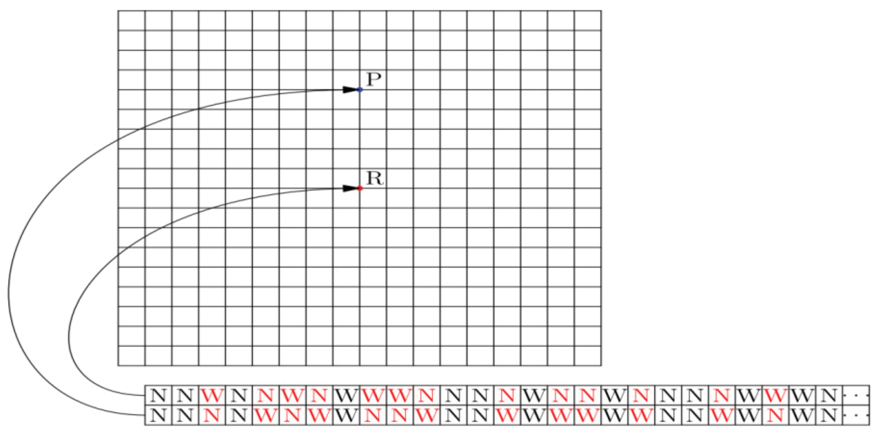

Fig. 5. Schematic showing the criterion for anticoincidence, from Gunturu and Schlosser [1]. R is the centre of the grid box under consideration. P is any example point in this subdomain. The binary sequences consisting of W and N show the presence or lack of sufficient WPD at the corresponding points. The times when the two points are in opposite wind-power states are highlighted in red.

Then a relaxed criterion is investigated: null-anticoincidence. The methodology employed is as the same as the one previously described. However, this time, only the instances when the center R of the box has no wind and the other P has wind are considered. These occurrences are then counted and if the count is at least 50% of the number of instances of no-wind at R, they are termed null-anticoincident. The number of such null-anticoincident points around R in a box of 19×19 grid points is finally logged as the score of R.

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