Spontaneous balancing of wind power in Western Europe: origin and limits

H. Flocard[1]

Abstract

Grounded on data from six Western European countries, the limits of natural balancing from the sum of wind power productions over several thousand-kilometre distances are investigated. We show that data and the associated balancing are satisfactorily reproduced using simple probabilistic laws. Observations and the subsequent analysis show that the hoped for smoothing of wind power production fluctuations does not happen. Consequently, the foreseen implementation of a high voltage network across national borders is not considered as a valuable contribution to overcome the drawbacks of wind power in the management of the national and European grids.

Introduction

"Wind is always blowing, somewhere". Although it seldom refers to quantized information, the statement sounds like solid common sense. It might even be true as far as the fuzziness associated with "somewhere" could apply to any terrestrial area as large as one might conceive. Now recently, this actually vague and consequently pointless sentence has been promoted to the rank of first principle by such official organizations as ADEME (French national) or the European Union (international). "Spontaneous wind power balancing" is thus endowed with the virtue of efficiently smoothing the electric production from wind mills over an entire country or a continent. Unfortunately, a major drawback of wind power, i.e. its intermittency, is thus underestimated. Actually, high level wind power is poorly predictable[2] and hardly manageable as shown nowadays in Germany. According to the natural balancing "theory", an erratic production in a given region would be compensated by the production of another region whose erraticism would undergo opposite fluctuations. Adding productions would result in a smoother behaviour. Such a smoothing would be badly needed since another major disadvantage of wind power is the extreme sensitivity to wind speed. Indeed, on a national scale, wind power may vary from 3% to 70% of the rated capacity within a few hours.

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[1] hubert.flocard@gmail.com The present document is a translation by Jean-Louis Bobin of a paper initially published in French a few years ago : *Nature et limite du foisonnement éolien*

[2] This is confirmed comparing 24h wind forecast with effective data for France as given on the site of the national grid manager RTE. For Germany see the site of the electricity exchange EEX.

Targeting the general public, the natural balancing concept is aimed at building up a positive image of wind power, both onshore and offshore. Actually it justifies ambitious and costly plans aiming at extending the high voltage grid, clearing borders over the whole of Western Europe. An assessment of its validity is therefore useful. Surprisingly, the same organizations that invoke balancing in order to support huge grid extension projects did not publish so far any analysis of its amplitude nor of its efficiency at curing the specific drawbacks of wind power production.

The present paper is intended at providing the missing analysis[3]. In order to do so, data describing wind power production for year 2012 will be used. They refer either to onshore and offshore wind farms in Denmark or to the cumulated wind power from six countries of Western Europe[4]. In section II amplitudes of balancing effects if any are reviewed. A closer look is devoted to the transition in production that occurs considering larger and larger geographical areas. The next step, section III, is a modelling of the data using purely stochastic methods. It is then shown through both observation and simulation that wind power production is random however large is the size of the considered European area. Furthermore the subsequent balancing appears limited.

II. Data

Figure 1 shows on an hourly basis the time history of the Danish offshore wind power capacity factor[5] in 2012. It looks very similar to the output of the Scottish wind farm Robin Rigg as observed in a previous study[6].

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[3] A similar study dealing with a 6 months period prior to year 2012 was proposed on the site of « Sauvons le climat » : intermittence et foisonnement

[4] Data analysed in the present document are extracted from the site of P.F. Bach, former technical manager of the Danish national power company. Mr Bach has collected these informations during several years from different European networks. Since whenever they are open to the public, the data are cast into different formats, Mr Bach put them on his site in a single standard format. Surprisingly, there is no such achievement at the European Commission level.

[5] The instantaneous capacity factor is the ratio between the actual power and the rated power P_i.

[6] See « Sauvons le climat », study « vent de mer, vent de terre» : Vent de mer, vent de terre

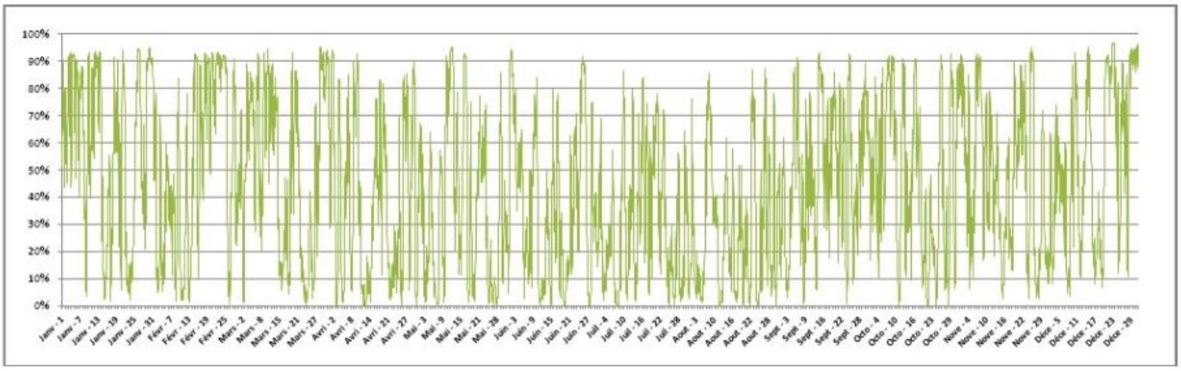

Figure 1. Capacity factor time history on an hourly basis of offshore Danish wind power for year 2012.

Rapid fluctuations of the capacity factor, from 0% to almost 100%, are observed. At first sight, the behaviour is the same as if a single wind mill with the rated power of the whole farm, i.e. about 900 MW, was operating. A closer look (see fig.4 below) shows an almost uniform distribution of the capacity factor over the range 0 to 95%, leading to an annual average of 44%. As anywhere in Europe, the highest production is obtained in the winter thanks to the many atmospheric depressions sweeping across the continent. That does not make it more regular: indeed, low production periods still occur. For instance, in the beginning of February 2012, a cold spell was prevailing in France causing a record electricity consumption with peaks over 100 GW. At the same time the domestic wind power was negligible[7], and power was imported from abroad. However according to figure 1, the power could not originate from Danish offshore wind farms, nor from British or German ones.

Figure 2 displays for 2012 the time history of the onshore Danish wind power capacity factor.

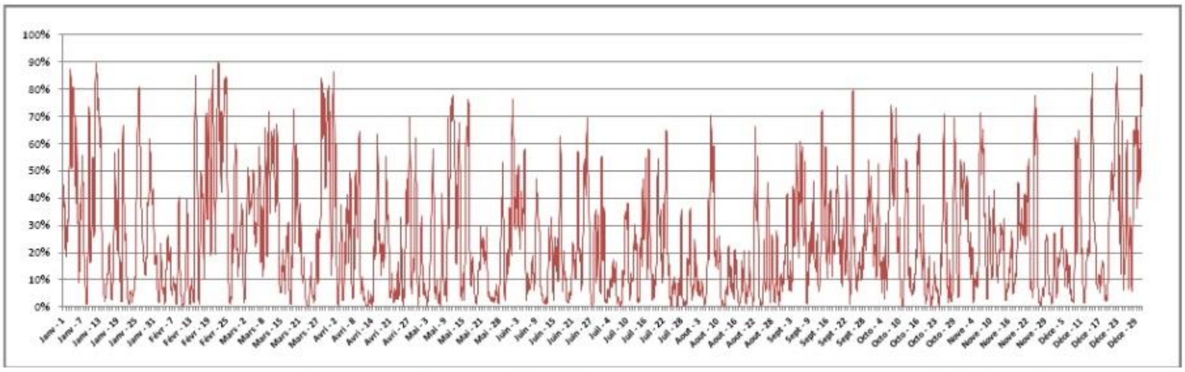

Figure 2. Capacity factor time history of Danish onshore wind power on an hourly basis for year 2012.

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[7] Concerning this critical period, see Intermittence et foisonnement de l’électricité éolienne en Europe de l’Ouest

Although the Danish onshore wind power is geographically concentrated, the behaviour differs both qualitatively and quantitatively from offshore. This effect stems from turbulences induced by a hilly landscape (despite a modest height) and the smaller size of individual mills[8]. Minima are still near zero whereas peaks are conspicuously lower and the average capacity factor is only 24.4%.

This is nevertheless a comparatively high value. In the same year 2012, the capacity factor was 23% in France and only 18% in Germany. Looking at the wind distribution in Europe (map in appendix 3), Danish wind farms, both onshore and offshore are situated in the most favourable region for wind power in Western Europe. I will come to this point later (section III).

Figure 3 shows, still on a hourly basis, the cumulated wind power of six European countries (onshore and offshore contributions from Denmark being accounted for separately). This is typically the kind of input grid managers would have to deal with provided the cross-border connexions where infinitely flexible (a situation sometimes dubbed “the European copper plate”). As evidenced on the figure, adding contributions from locations that might be 2000 km away from each other does not result in a regular production, contrary to what the natural balancing “theory” suggests.

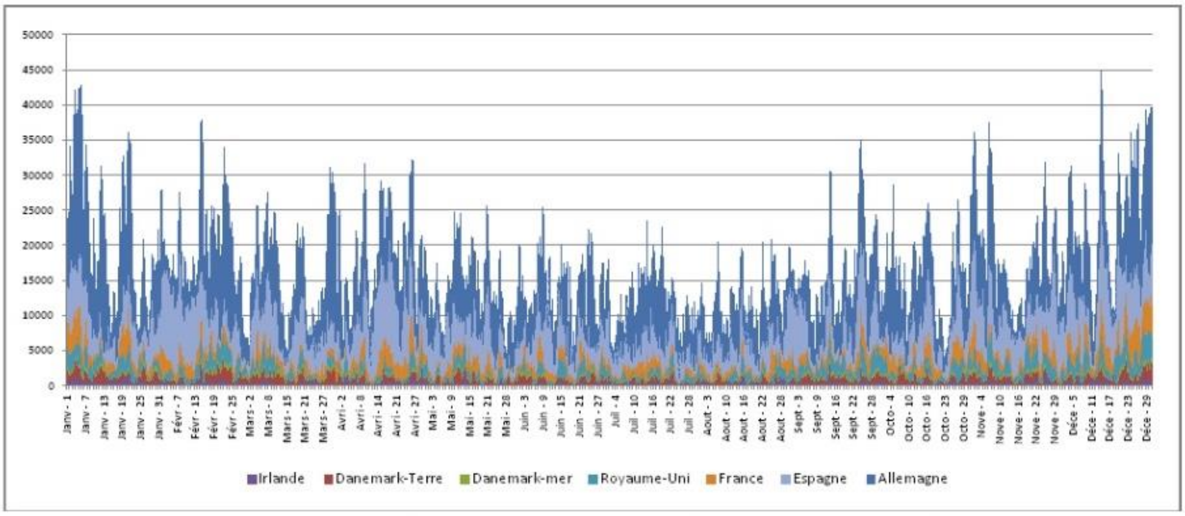

Figure 3. Time history of cumulated wind power from 6 Western European countries. Powers given in megawatts.

Actually, given an installed capacity P_i growing from 68 to 75 GW along the year 2012, the cumulated production of the six countries oscillates randomly between a minimum 1.3 GW (2.3% of P_i) and a maximum 45 GW (63% of P_i). The continental average capacity

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[8] Furthermore, the technology is comparatively old.

factor is 21%. Along a given month or even on a given day large fluctuations are visible. Another study will unravel further properties of these variations and anticipate consequences of European wind power policies provided they are effectively enforced.

This paper is focused on the origin and the amplitude of natural balancing. Emphasis is put on capacity factor distributions derived from figures 1, 2 and 3, as shown on figure 4 for onshore and offshore Denmark and the whole of Western Europe. In each case, the percentage of hours (with respect to the 2012 year: 8784) during which wind power is delivered in the intervals 0-5%, 5-10%… 95-100% of the installed capacity, is plotted.

The offshore Danish wind power (red curve) exhibits a comparatively flat distribution. However less than 10% of its potential production is delivered during nearly 10% of the time. This fact contradicts the familiar assertion “wind is more constant at sea”, a point one can also make after inspection of figure 1.

The distribution of onshore Danish wind power (green curve) is monotonously decreasing. The capacity factor is below 10% during nearly 20% of the time.

The same plot for the whole of Europe (blue curve) is more like the distribution for a single mind mill. Starting from zero, it exhibits a peak close to the European annual mean value (21%). The capacity factor is below 10% during nearly 15% of the time. Altogether, the European wind power surpasses 50% of the cumulated rated power for only 1.6% of the time.

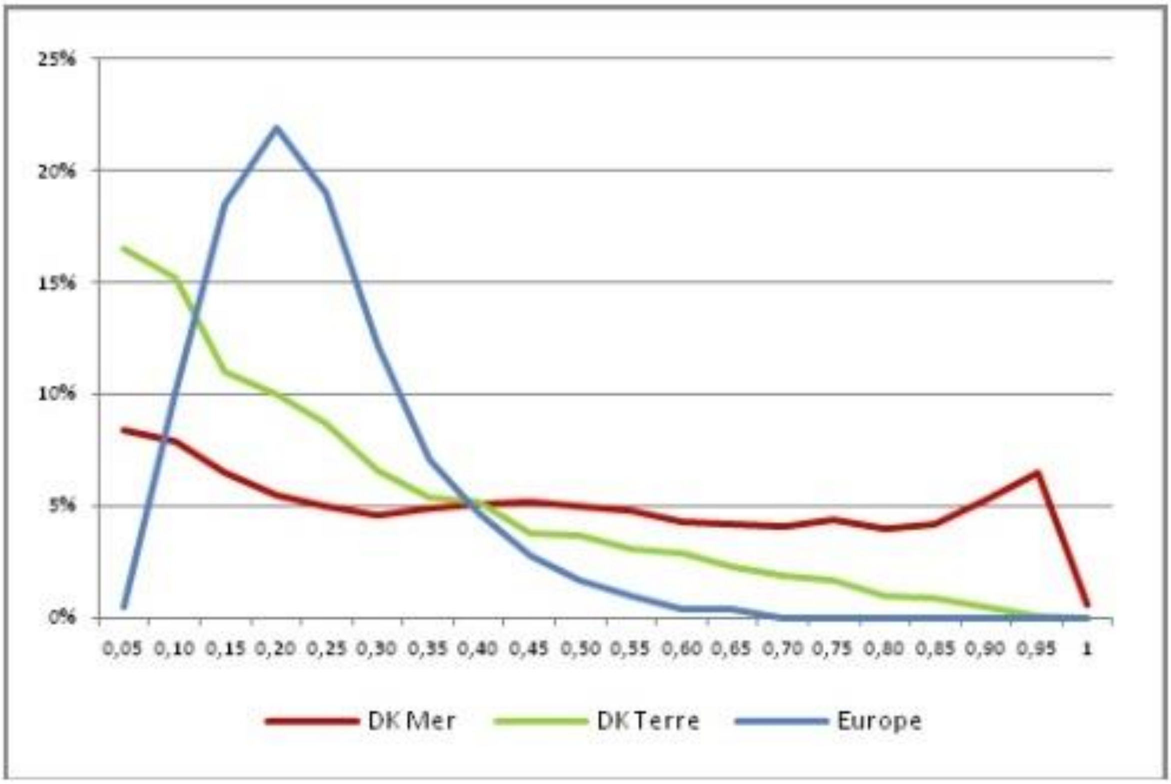

Figure 4. Wind power capacity factor time distribution. Percentage of time during which a given capacity factor (within a 0.05 interval) prevails. Red: Danish offshore. Green: Danish onshore. Blue: 6 European countries.

The behaviour of wind power duration curves is shown on figure 5. The hourly powers are plotted successively according to decreasing values. In order to compare with previous figures, the hourly power values are normalized after division by the average annual power. Consequently, the crossing point of the power duration curves with the line at ordinate 1 gives the number of hours during which the power is above average.

The offshore Danish power duration curve is almost linear whereas the Danish onshore curve is consistently concave. The European curve is concave at high power and convex at low power. It crosses the line at ordinate 1 at about 3800 hours i.e. less than half the yearly total. This means that the European wind farms most of the time deliver less than average power.

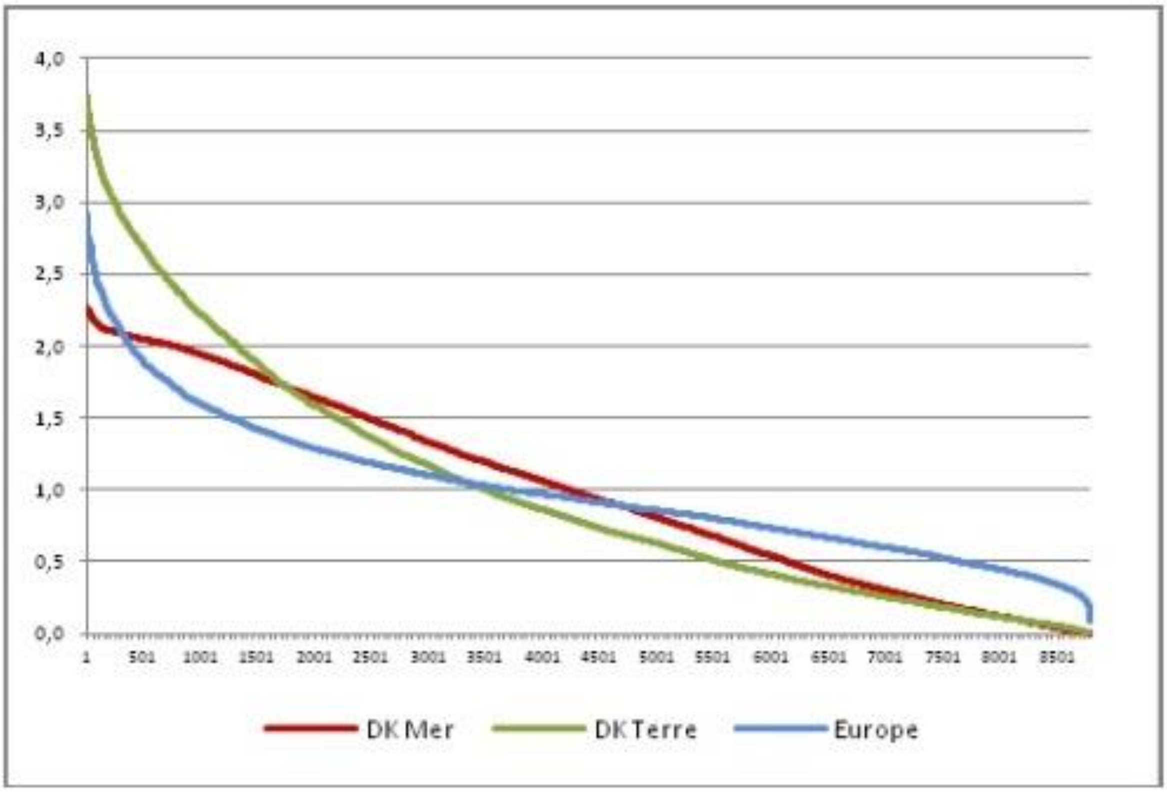

Figure 5. Normalized power duration curves for Danish offshore (red), Danish onshore (green) and 6 countries (blue). Ordinate 1 corresponds to the annual mean value.

III) Probabilistic modelling

The behaviour of the European wind power production is reconstructed using a summation of random variables as explained in appendix 1. In this appendix, 8 regions are identified whose productions are simulated for every one of the 8784 hours of year 2012 by random variables that add to the total as was done for figure 3. The corresponding distribution (blue curve on figure 6) mimics fairly well the experimental distribution displayed on figure 4.

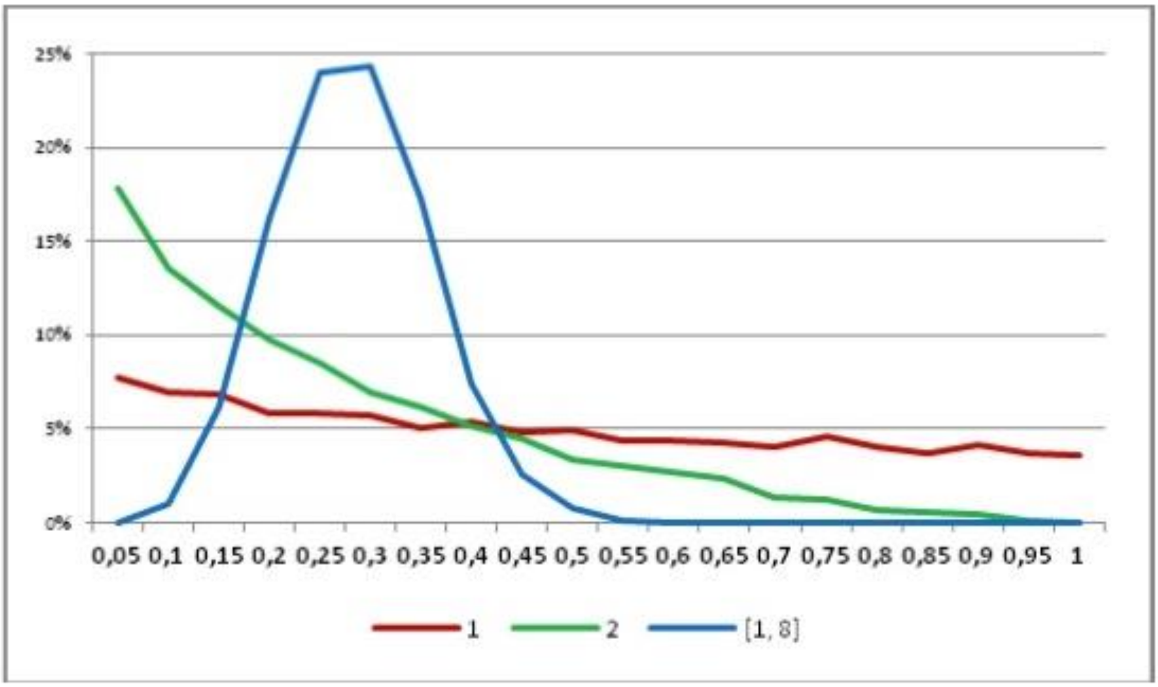

Figure 6. Reconstructed time distribution curves after the probabilistic modelling. The behaviours of "Regions" labelled 1 and 2 are close to actual in Danish offshore and onshore wind farms respectively. The curve labelled [1,8] represents the density of probability associated with the sum of 8 independent "regions" simulating the whole of Western Europe (see appendix 1). Every point on the curves represents the probability for the variable to be located in an interval 0.05 wide.

The curves on figure 6 were obtained after 70278 random draws. It turns out that the result does not depend upon the choice of a specific probability law as explained in appendices 1 and 2 in which the statistical stability is discussed. The reconstitution of the observed behaviour is obtained through any other choice. In the case of regions labelled 1 and 2 in appendix 1, random draws from actual Danish distributions both offshore and onshore were used (green and red curves on figure 6). Similar results would apply to a region with homogeneous wind conditions; however the necessary production data have not been made available[9].

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[9] It is worth noticing that in France, the hourly production of every conventional power plant (nuclear, coal fired, gas and oil fuelled) and of every hydroelectric dam is immediately available on the site of RTE. Although they are subsidized by consumers via CSPE wind and solar farms are not committed to publish their data. Consequently they don't.

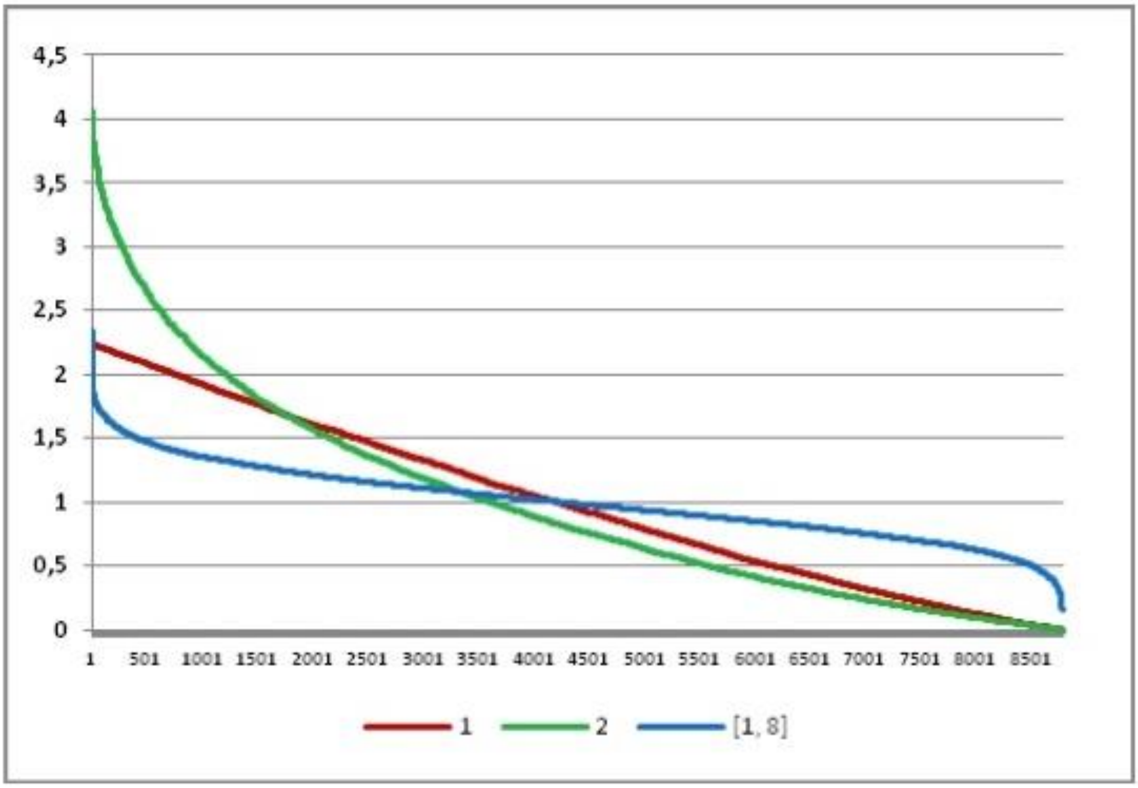

Figure 7. Reconstitution along 8784 hours of power duration curves after Weibull distributions in "regions" 1 and 2. The curve labelled [1,8] represents the cumulated production of 8 "regions" (see text).

As a final check, the reconstructed power duration curves (figure 7) also show a fair agreement with reality (figure 5)[10].

A closer look at the blue curves in figure 4 and 6 evidences some differences. Although the reconstruction on a probabilistic basis gives a correct overall picture of the natural balancing, the smoothing effect is overestimated. Wings on both sides of the peak value are more important in figure 4 than in figure 6. In real life, extreme events occur more often than predicted by probability laws. Either high gusty winds or long calm periods take place almost everywhere at the same time in Western Europe. For such events which might induce management problems on the grid, dividing the continent into 8 independent regions whose wind power productions would balance one another looks rather optimistic. The division might be irrelevant whenever anticyclonic conditions or depressions exist at the synoptic scale. By and large the correlation level of wind power production in real life is higher than in the model. Balancing effects that would occur provided a high voltage super grid is implemented are reduced accordingly.

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[10] On both figures 5 and 7, every power duration curve was normalized with respect to the average value stemming from the 8784 random draws.

IV) Conclusion

Using wind power data, this paper is an attempt at evaluating to what extent adding wind power productions from six Western European countries would result in reduced fluctuation amplitudes with respect to local ones.

Observations for year 2012 show the effect is real. However the time history of the cumulated European wind power production still exhibits steep ramps and large fluctuations of the capacity factor from 2.3% to 63% with an average of 21%. A further study is under way investigating more thoroughly this behaviour.

From merely inspecting the data, it appears that the costly implementation of new high voltage lines the wind power industry is lobbying for at the European Commission[11], is to be of limited efficiency to mitigate the grid instabilities generated by a production with large random fluctuations.

We showed that in first approximation, some “smoothing” is correctly reconstructed after probabilistic laws. Now, since the behaviour of the capacity factor of a single windmill or of the wind power in a region where winds are strongly correlated, independently from other regions, is described by random variables, the laws tell us two things:

1) The sum of random variables is still a random variable. Adding random variables does not suppress randomness
2) The distribution evolves towards a universal shape as predicted by the central limit theorem.

Independence of random variables (wind power from distant regions) does not remove randomness from their sum. Actually, imperfections in the mathematical model lead to an overestimated smoothing. Indeed, the model predicts a larger than real lessening of extreme highs and lows in wind power production. Correlations of wind power are observable over hundreds of kilometres and in some cases the range is over a thousand kilometres. Fluctuations in amplitude are conserved accordingly. Only systematic anti correlations (never observed in Europe) would diminish the fluctuations.

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[11] On October 14th 2013, the European Commission presented the list of 248 « projects of common interest » with high priority for electricity, gas and oil networks in the community of 28 nations. Among them were grid extensions aimed at managing intermittent power sources.

As is well known in electrical engineering a feedback can be used to ensure the mitigation of a random behaviour. In the power sector this is done by conventional power plants (brown coal, coal, gas, nuclear) and by hydroelectric dams, all sources to be used by grid managers, the more so in the future.

As a final remark, the present study shows that in Europe the reliability of a massive wind power production will be subject to chance. A fact that should be collectively accepted.

Acknowledgements

The author thanks the late P. Bacher and J.P. Pervès, M. Petit, F. Poizat, B. Tamain for their careful reading of the manuscript and useful suggestions.

Appendix 1

Random wind power production simulation

In this appendix, random draws are exclusively used in order to reproduce the properties of wind power as presented in the main text.

Since independent random draws are sought, the geographical correlation level is to be estimated first. Indeed, look at satellite images as presented every night on TV within weather forecast shows. Conspicuously, the correlation range of air flows appears larger than 500 kilometres. As a consequence, there is no point in looking for a natural balancing effect within such distances. Wind properties are spread homogeneously but for time delays (typically one hour) due to the motion of frontal zones.

This can be evidenced after figure A1.1 which shows, for July 2013, the capacity factors of the Spanish and French wind powers. In Spain wind farms are mainly located in the central “meseta” whereas in France, most wind farms are located north of the river Loire, i.e. more than a thousand kilometres away. As one may notice, time evolutions of the capacity factors look similar on a day to day basis and partly similar on a weekly scale. Indeed, in Summer, the Azores high is displaced and extends over most of Western Europe. This fact precludes natural smoothing and casts some doubts on European studies recommending massive interconnection between France and Spain on behalf of the complementarity of wind regimes[12]. This remark does not apply to Winter time. Then, the high extends over the Atlantic ocean and France shares the wind regime prevailing in Ireland and southern England.

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[12] In some of its scenarios, highly dependent on renewable electricity, the « roadmap to 2050 » of the « European climate foundation » considers 27 GW or more of high voltage connection across the France -Spain border. Now after a 20 year struggle, the connection between the two national networks increased from 1 to 2 GW. Social oppositions to overhead power lines, lead to consider costly submarine cables for the next connection to be implemented.

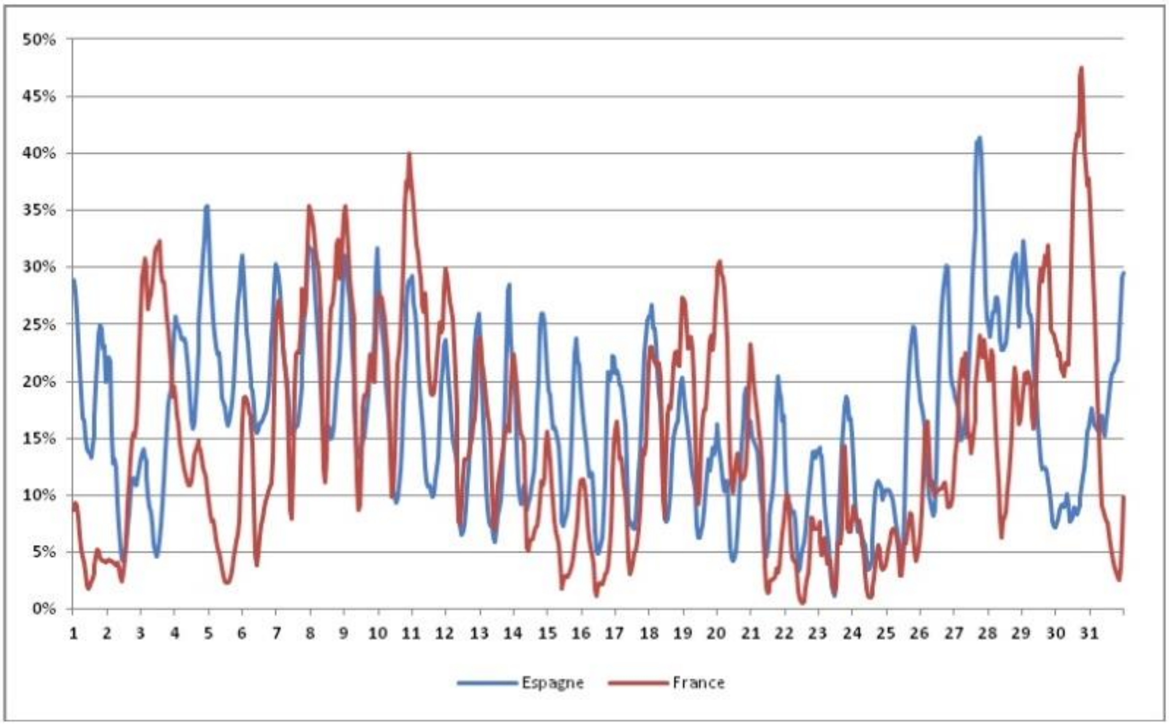

Fig. A1.1. Time history of wind power capacity factors in France and Spain during July 2013. Data are taken from Red Electrica Espana for Spain and eCO2mix (RTE) for France.

Now, consider those parts of Europe and neighbouring seas where the average wind is strong enough for the implementation of energetically suitable windfarms. They are not so numerous: northern Spain, north western France, Ireland, Great Britain, the Channel and the North sea up to Norway. To these large areas, smaller spots such as Roussillon in France and the Strait of Gibraltar, can be added. In the following, only 4 independent high potential wind power zones extending over 500 kilometres, i.e. a total of 1 million kilometres squared, are thus taken into account.

However, European data include wind power from low productivity regions: central and southern Spain, central and eastern France, Switzerland, central and southern Germany. Although it was not energetically advisable to implement wind farms in such places, generous subsidies and feed in tariffs made them highly profitable. Altogether, despite the contribution of windy regions, “Languedoc-Roussillon”, Brittany and “Nord-Pas de Calais”, the capacity factor of wind power in France stays below 24%. Indeed, an important part of wind power is located in regions with poor wind power potential: “Champagne-Ardennes”, “Picardie” and “Lorraine”. Similarly, the average capacity factor of the terrestrial wind farms in Germany stays below 20% (18% in 2012). Due to present policies and administrative support aiming at developing wind power[13], these regions are and will remain an important component of European wind power. Consequently, in the present study, wind mills poorly productive in 4 independent regions (another million kilometres squared) are also to be included.

A probabilistic analysis can now be performed, dealing with wind power implemented within 8 homogeneous independent regions extending over 2 million kilometres squared. In each region, 366x24 (= 8784) independent random draws are made after a Weibull distribution, thus simulation wind power production on an hourly basis for the whole year 2012.

The Weibull distribution (see appendix 2) depends upon 2 parameters: the exponent k is the shape parameter; λ is the scale parameter allowing the choice of the average for the capacity factor. As shown on figure 6, choosing $\lambda = 0.8$ for “region 1” yields a distribution close to the actual Danish offshore wind power as displayed on figure 4. In both cases, the mean value is 44%. Choosing $\lambda = 0.3$ in “region 2” yields a distribution mimicking the Danish onshore wind power with a mean value 24% close to actual. For regions 3 and 4 with a high wind power potential, λ was drawn from the interval [0.3, 0.8]. To simulate regions 5 to 8 with reduced wind power potential, λ is drawn from the interval [0.15, 0.3] leading to a capacity factor between 15% an 24%.

In appendix 2, plots represent 70278 random values. Elements of statistical analysis showing the stability of the results with respect to the size of the set of random values are given. The results also appear unaffected by the number of independent regions but for a slight attenuation of the smoothing in the case of the smaller number investigated.

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[13] For instance, in France, the government is willing (2013) to exempt wind farms from the ICPE environmental classification.

Appendix 2:

Weibull distribution and wind power

The probability law introduced by Weibull[14] has many strong points. On the one hand, it is very flexible since it includes in its definition 2 parameters k and λ (see below). It can thus represent classical and not so classical probability densities. An example of the latter is the Danish offshore or onshore wind power. On the other hand, the analytical formulation is simple and easy to deal with[15] over any interval in which the random variable is located. In our case the wind power capacity factor lies in the interval [0, 1].

The following formula was used for the cumulative Weibull distribution:

$$p(x) = 1 - e^{-(-\frac{\ln(1-x)}{\lambda})^k}$$

where p(x) is the probability for the random variable to be smaller than or equal to x. Both x and p(x) are in the interval [0,1].

In the investigations reported in section 3, the shape parameter k was 0.9. As shown with the green and red curves on figures 4 and 6, this choice leads to a convenient simulation of the capacity factor distributions of the Danish offshore and onshore wind power and yields correct mean values, provided λ is chosen to be 0.8 and 0.3 respectively.

Once distributions in regions 1 and 2 of the numerical analysis are defined according to the above prescription, the other regions are simulated. Random values for λ are chosen in the interval [0.3, 0.8] for the 2 other regions with high potential and in the interval [0.15, 0.3] for the 4 low potential regions. After the central limit theorem, λ values have little influence on the final capacity factor distribution of the simulated “Europe” cumulating the 8 regions. Figure A2.1 shows the 8 simulated capacity factors. Mean values vary between 24 and 44% in the most productive regions, between 15 and 24% in the less productive ones.

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[14] For more details see e.g. http://fr.wikipedia.org/wiki/Loi_de_Weibull

[15] All results in the present paper appearing in figures 6 and 7 were obtained using a standard spreadsheet. A 35 characters expression was written and pasted into the 70000 cells necessary to complete the analysis.

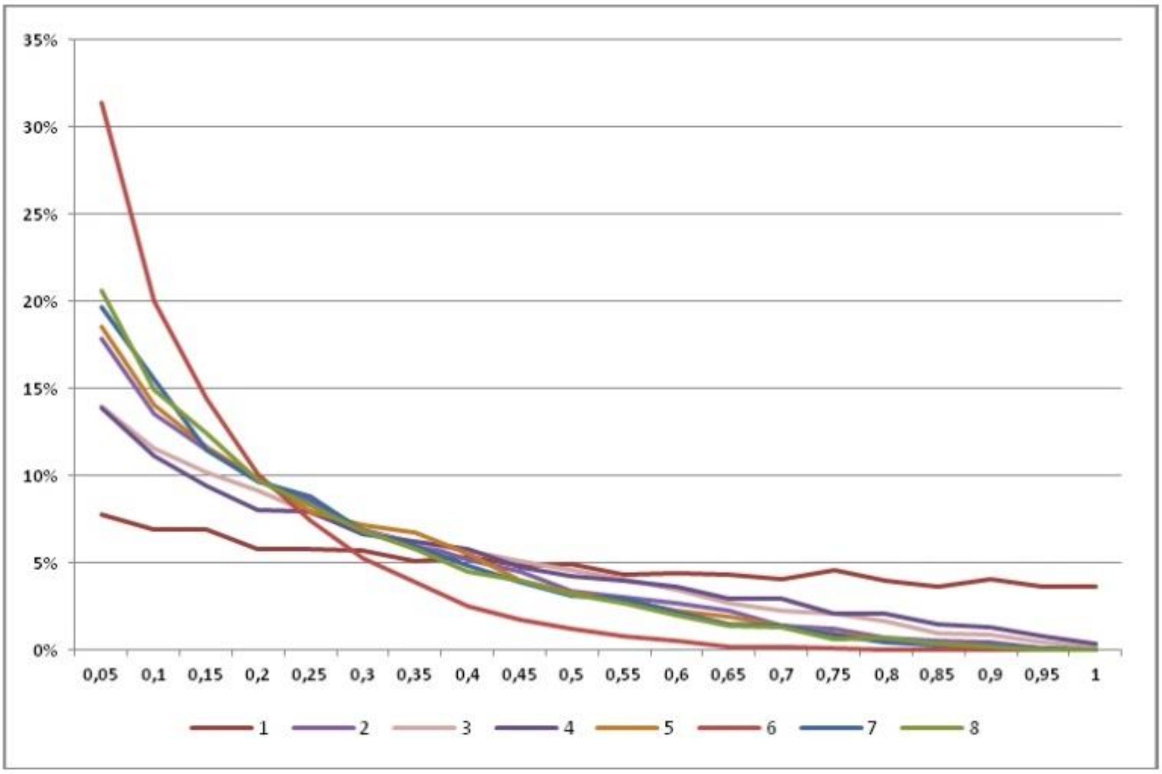

Figure A2.1. Simulated capacity factor distributions for each of the 8 "regions" accounted for in section III.

In order to set up figures 6, 7 and A2.1, 70278 random values were drawn. Another draw of the same size would have given a slightly different result. To illustrate the statistical stability of the present analysis, the dispersion amplitude from 10 successive draws is shown on figure A2.2.

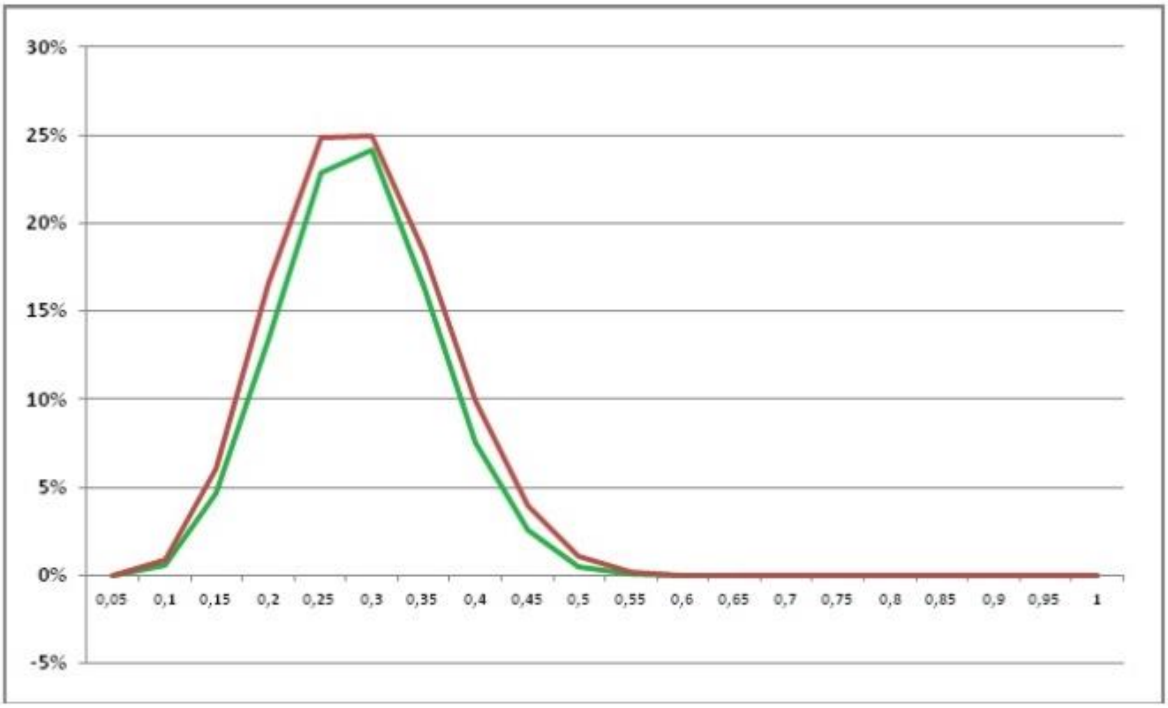

Figure A2.2. Statistical uncertainty zone for distribution [1,8] (blue curve on figure 7) as calculated after 10 successive random draws. Curves represent the distribution [1,8] plus (red) or minus (green) the standard deviation calculated for each point.

Appendix 3

European wind map

Figure A3.1 is reproduced from a document issued by VESTAS, a Danish industrialist specialized in wind power. Colours represents expected wind strengths 80 meters above ground or sea level.

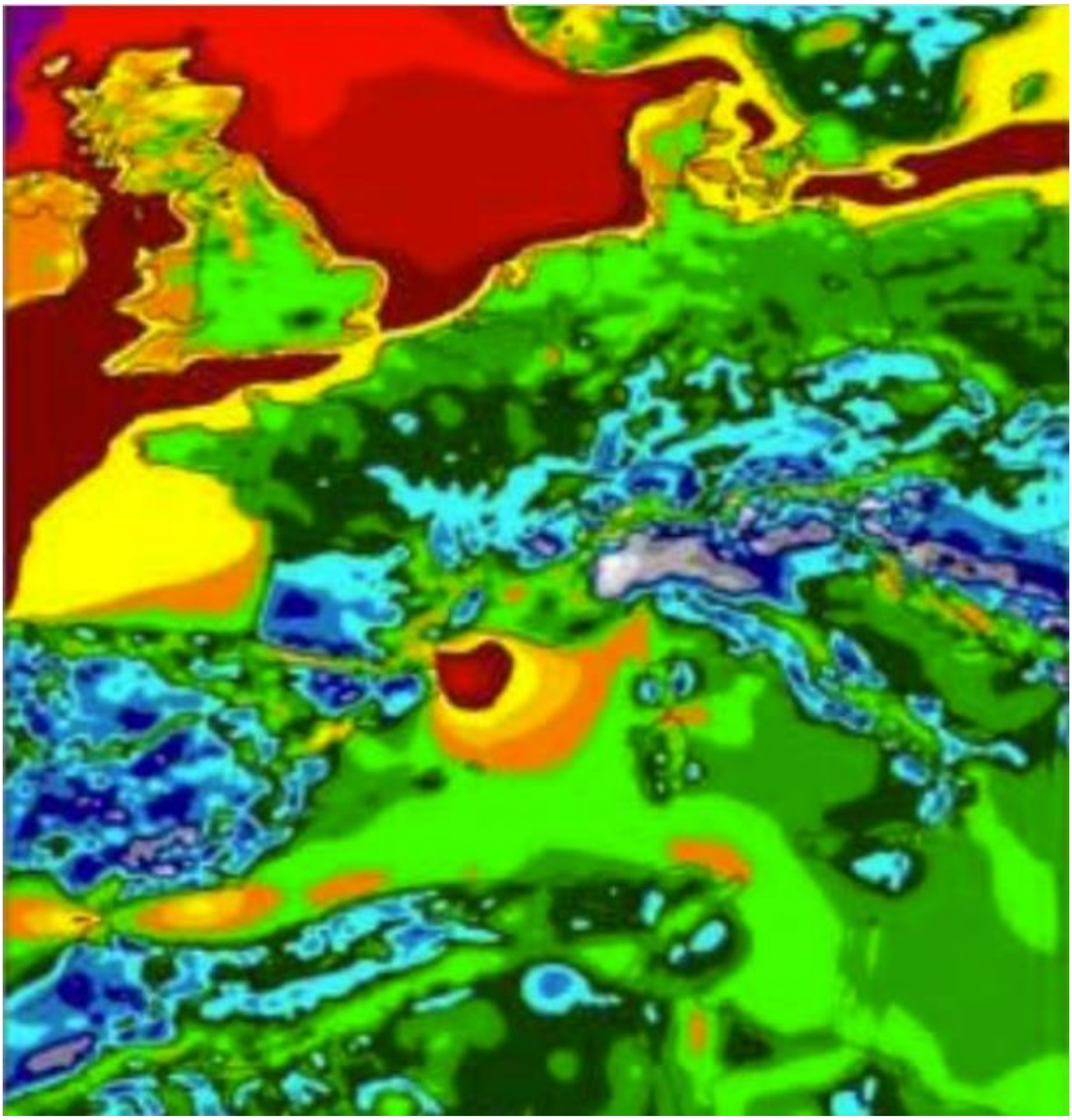

Figure A3.1. Yearly average wind strength in decreasing order: light red, red, dark red, yellow, orange, green, dark green, light blue, dark blue. (source VESTAS)

Danish wind farms are located in the more favourable zones (dark red). The statement also holds for the Scottish wind farm Robin Rigg (see note 6).

According to this map, in France the best zones are in Brittany, along the Channel, in "Roussillon" and the Rhone valley. On the contrary, poor wind conditions in regions "Champagne-Ardennes", "Lorraine" and "Centre" hardly justify on energetic grounds wind power implementation. Voluntarily developing wind power everywhere in France in order to ensure local "energy independence" will be confronted with large differences in wind potential.

It is worth noticing that no offshore wind farm as planned in Brittany and Normandy is located in a zone as favourable as in the Danish case. Actually they will be situated in the yellow area in the above map. On the contrary, Irish, Scottish, Danish and German offshore wind power benefits from the highest potential of the red areas shown on the map. Further French wind farm implementation in offshore regions with heavy winds looks unlikely since it might meet various constraints: zones excluded due to the marine traffic in the Channel, technical difficulties associated with too deep waters off Brittany and "Roussillon", usual hostile conditions in a marine environment. By and large, the economic profitability of French offshore wind power is questionable.