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RESEARCH ARTICLE

A spatial and temporal correlation analysis of aggregate wind power in an ideally interconnected Europe

A. Malvaldi[1], S. Weiss[1], D. Infield[1], J. Browell[1], P. Leahy[2] and A. M. Foley[3]

[1] Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK
[2] School of Engineering, University College Cork, Cork, Ireland
[3] School of Mechanical and Aerospace Engineering, Queen's University Belfast, Belfast, UK

ABSTRACT

Studies have shown that a large geographic spread of installed capacity can reduce wind power variability and smooth production. This could be achieved by using electricity interconnections and storage systems. However, interconnections and storage are not totally flexible, so it is essential to understand the wind power correlation in order to address power system constraints in systems with large and growing wind power penetrations. In this study, the spatial and temporal correlation of wind power generation across several European Union countries was examined to understand how wind 'travels' across Europe. Three years of historical hourly wind power generation data from 10 countries were analysed. The results of the analysis were then compared with two other studies focused on the Nordic region and the USA. The findings show that similar general correlation characteristics do exist between European country pairs. This is of particular importance when planning and operating interconnector flows, storage optimization and cross-border power trading. Copyright © 2017 The Authors Wind Energy Published by John Wiley & Sons Ltd

KEYWORDS
wind power generation; wind energy; interconnection; geographic diversity; correlation

Correspondence
A. Malvaldi, Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK.
E-mail: alice.malvaldi@strath.ac.uk

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1. INTRODUCTION

Installed wind power capacity in Europe grew strongly in the decade to 2015, from 48 GW, at the end of 2005, to almost 142 GW by the end of 2015.[1] As the penetration of wind generation in power systems continues to increase, the uncertainty and variability associated with wind power bring challenges for power system operators. Many previous studies have addressed the problem of integrating variable wind power in existing power systems.[2–5] These works emphasized the impact of geographic diversity of wind farms on power system operations. A large geographic spread of wind capacity greatly reduces the aggregate wind power variability, as wind speeds experienced in different areas are not 100% correlated over time. As the geographic spread increases, the distribution of aggregate wind power approaches a normal distribution according to the central limit theorem.[6] As a result, the number of high-power or low-power output events in the aggregate wind power time series is decreased, and this reduction in variability is referred as the 'smoothing effect'.

The smoothing effect has been the focus of numerous studies.[6–15] For example, large geographical dispersal of installed wind power capacity has been shown to be beneficial to power system operators in the study of Giebel.[7] Several studies have also observed that linear cross-correlation coefficients of wind power output between pairs of wind farms or at system level decrease exponentially with increased separation between the wind farms or systems.[6,8–12,14,15] Hasche[12] shows that the smoothing effect depends only on the region size and not on the number of wind farms. The correlation of wind power output between wind farms is influenced not only by separation distance but also by time scales. High-frequency variations of wind power from different locations are random and uncorrelated, whereas correlation is high for longer term fluctuations (several hours or more).[6,8,10,16] Moreover, the degree of correlation between wind farm outputs is also influenced by diurnal weather variations and the movement of synoptic weather systems. Therefore, the correlation of wind power output between different locations can exhibit a wide range of values from 1 day to another. Two locations can have a very high correlation 1 day and little or negative correlation the next.[6,10,17]

Many other factors may impact on the level of correlation between the power outputs of different wind farms. One of these is the direction of separation between wind farms. There may be a greater similarity between outputs of wind farms separated in one direction than in others, as shown in Tastu *et al.*[18] and Osborn *et al.*[19]

In general, increased geographic diversity of wind power capacity and increased numbers of turbines may deliver several benefits to power system operators. For example, the number of ramp events tends to decrease as the geographic diversity of installed wind power capacity increases.[6,11,16,20,21] The relative requirement for ancillary services may also be reduced because of the smoothing effect on aggregate wind power outputs, as shown in the analysis carried out by Ernst *et al.* using data from the German '250-MW measurement program'.[8] Furthermore, geographic diversity and larger numbers of turbines both lead to a lower temporal variability of aggregate power output, with decreased durations of high-power and low-power events, and smaller wind forecast errors. However, high penetration of wind power also brings some issues and challenges for transmission system operators (TSOs). Frequency control and system security are highly influenced by wind power fluctuations in systems with very weak interconnection.[22–24] For example, on the island of Ireland, there is 10.26 GW of dispatchable generation capacity, including 3.02 GW[23] dispatchable wind plant and 950 MW of interconnection capacity to Great Britain (GB). The TSOs in Ireland EirGrid and System Operator Northern Ireland (SONI) have increased interconnection to the UK and between Northern Ireland and the Republic of Ireland with further plans to extend to France to ensure security of supply and grid stability.[25] EirGrid and SONI[25] identified and examined the technical operational issues with increasing wind penetration.

It is therefore desirable to encourage greater geographic diversity of wind power capacity. Several studies have examined the opportunity to 'smooth' wind generation over time and to integrate it more efficiently and have suggested a common balancing area for adjacent systems.[4–6,26] As a result, interconnection capacity between different countries and market regions within the European Union (EU) and the USA has been increasing over the last number of years. For example, within the EU, more than 20 GW of electricity interconnections have been built during the last decades and more than 50 GW are under construction or planned to be built, according to the projects of common interests (PCI).[27]

A few studies have analysed the correlation between wind farms using actual wind power production data. Among them, Holttinen[11] used real power production data from the Nordic countries of Denmark, Finland, Sweden and Norway to perform a statistical analysis. However, in this study, the time series from Finland, Sweden and Norway had to be upscaled more than 10-fold to create large-scale wind power production time series. This study found that increased geographical spread of wind power capacity reduces the overall variability, and in particular, the number of periods of very high and very low outputs decreases. A more recent study conducted by Louie[6] carried out extensive correlation analysis using historical data from four North American system operators (i.e. BPA, ERCOT, MISO and PJM). In the study, a hypothetical interconnection of the normalized wind power values for four North American systems is modelled. Louie[6] highlighted three main conclusions. First, all correlations between systems or wind farms present similar characteristics such that correlation increases with the averaging period and decreases exponentially with separation distance. Second, despite the smoothing of wind generation over time by spatial aggregation, clear diurnal and seasonal patterns were still evident in the aggregated wind generation time series. Third, the increase in installed wind power capacity did not affect the correlation and statistical results of the study.

Foley *et al.*[26] analysed meteorological wind data from a number of Met Éireann and UK Meteorological Office recording stations in the UK and the Republic of Ireland in order to examine wind variability across the British Isles. The situation in the British Isles regarding interconnected power systems is somewhat similar, albeit at a smaller scale, to the North American case.

In this study, the analysis by Foley *et al.*[26] is extended to wind power generation data from different countries in the EU. Historical wind power data from 10 different EU Member States are used to carry out an extensive statistical analysis across yearly, daily and hourly time-scales. The results are then compared with two previous studies by Holttinen[11] on several Nordic countries and Louie[6] on four North American system operators. The study aims to investigate the impact of an 'ideally interconnected Europe' modelled as the average wind power production of 10 selected EU countries, similar to the hypothetical interconnection of the normalized wind power values modelled by Louie[6] for four North American systems. The paper is organized into five sections. The background is overviewed in Section 1. The datasets used for the study are described in Section 2. The statistical analysis methods are presented in Section 3. The results are discussed in Section 4, and the conclusions drawn are provided in Section 5.

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2. DATASET

This study used historical data of wind power generation from 10 European countries (i.e. Austria, Belgium, Denmark, Germany, Great Britain, Ireland, Italy, Romania, Spain and Sweden). The analysis considered a 3 year period starting on 1 January 2012 and ending on 31 December 2014. Table I lists the time resolution and data source for each country selected.

The datasets collected have different time resolutions, ranging from 5 min up to 1 h. Thus, the original time series were aggregated hourly, temporally synchronized and referenced to Greenwich Mean Time. Figure 1 presents a map of Europe with the 10 countries, which are the focus of the analysis, highlighted in grey. The installed wind power capacity (MW) for each of the 10 countries and the position of *weighted centroid* (i.e. blue circle) together with operational, under construction and planned PCI high-voltage direct current interconnectors[27] are also shown.

The 10 countries were selected not only because of the availability of datasets but also because of the following: (i) geographic diversity (i.e. terrain, size and location) on a north–south axis; (ii) the different installed wind power capacity values; and (iii) the existence of inter-country PCI high-voltage direct current interconnections.[27] In addition, the geo-

Table I. Time resolution and source of wind power data for the 10 EU countries selected for this study.

Country	Time resolution	Source
Austria (AT)	15 min	Austrian Power Grid (APG)[33]
Belgium (BE)	15 min	Elia[34]
Denmark (DK)	1 h	Energinet.dk[35]
Germany (DE)	15 min	TransnetBW GmbH,[36] TenneT,[37] 50 Hertz Transmission GmbH[38] and Amprion GmbH[39]*
Great Britain (GB)	5 min	Gridwatch[40]
Ireland (IE)	15 min	System Operator Northern Ireland (SONI)[41] and EirGrid[42]
Italy (IT)	1 h	Terna S.p.A. - Rete Elettrica Nazionale[43]
Romania (RO)	10 min	Transelectrica[44]
Spain (ES)	10 min	Red Eléctrica de España (REE)[45]
Sweden (SE)	1 h	Svenska Kraftnät[46]

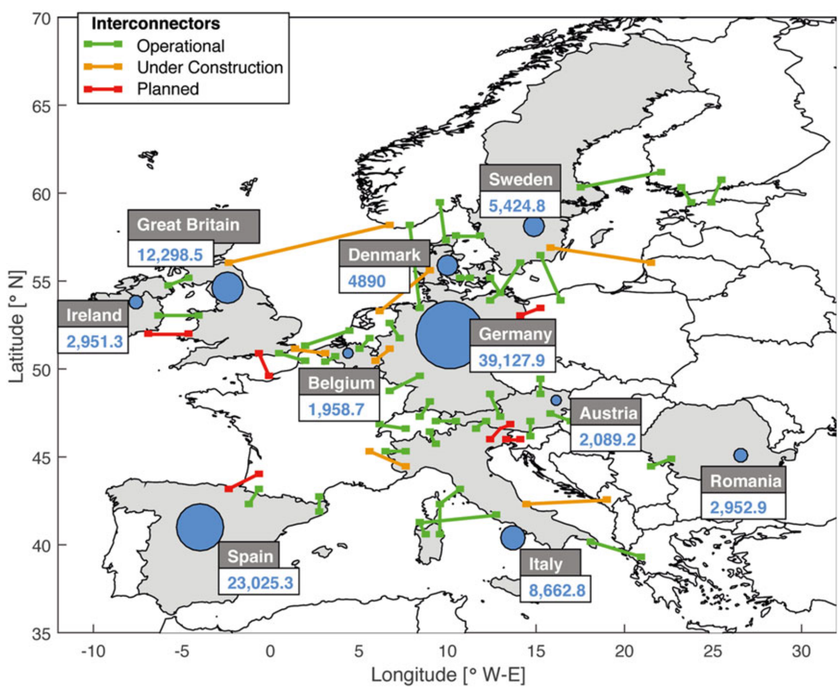

Figure 1. Map of Europe showing the 10 selected countries for this study, their installed wind power capacity (MW) and position of weighted centroid (blue circle), together with the main electricity interconnectors from the PCI.[27] [Colour figure can be viewed at wileyonlinelibrary.com]

*Data from all the TSOs are based on a projection of the feed-in values of representative wind farms that are measured online.

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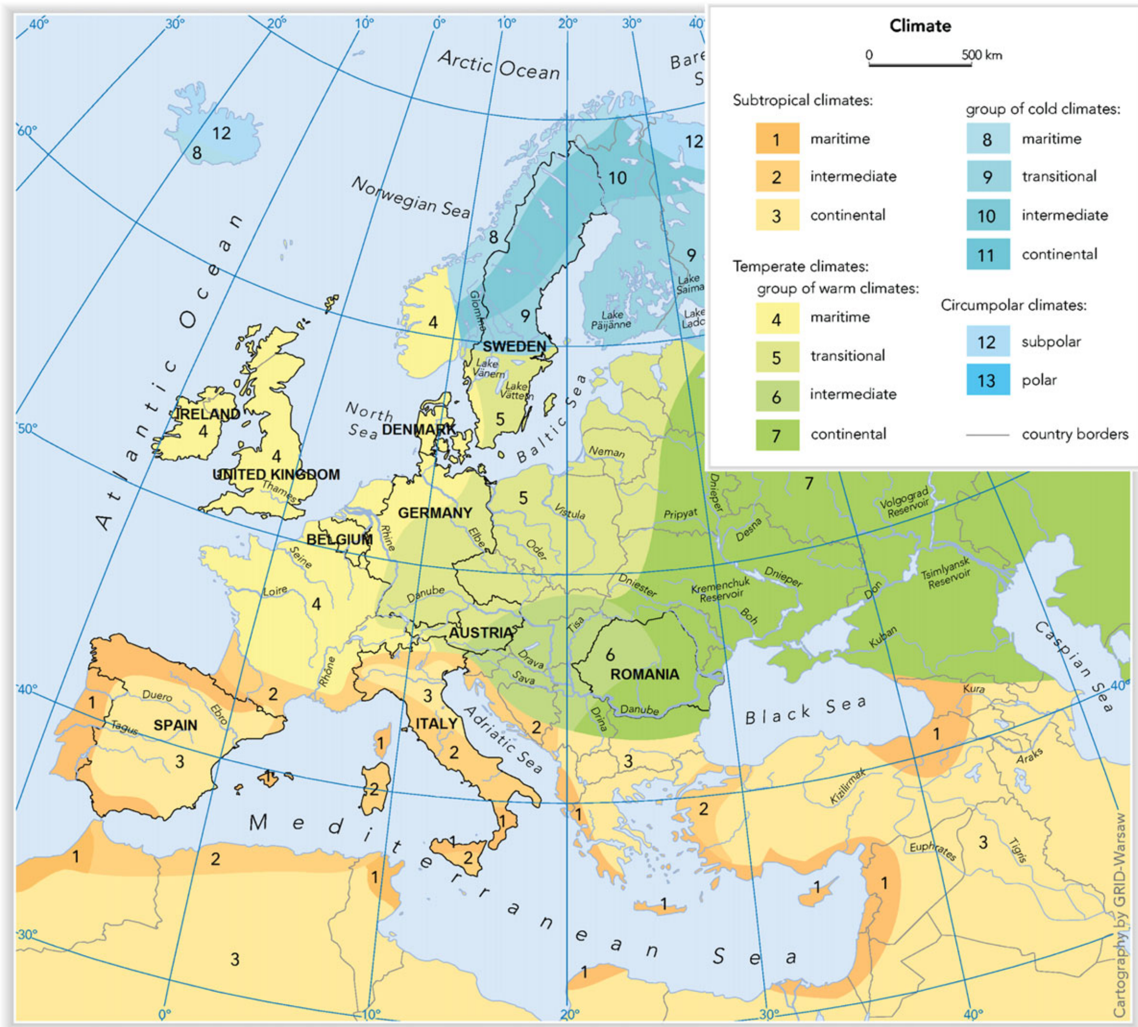

Figure 2. Map showing the main climates of Europe[29]; the 10 countries considered in this study are labelled by their names. [Colour figure can be viewed at wileyonlinelibrary.com]

graphic diversity allows for very different weather systems and climates among the selected EU countries. The climatic conditions range from subtropical climates, temperate climates and cold climates[28,29] as shown in Figure 2.

Table II shows the installed wind power capacity for each EU Member State at the end of 2012, 2013 and 2014, according to the European Wind Energy Agency statistics annual reports.[1,30,31] The 10 countries selected for this study are highlighted in Table II. The total installed wind power capacity of these 10 countries was 103,019 MW at the end of 2014, which was 79.82% of the total installed wind power (i.e. 129,060 MW) in the EU in 2014.[1,32] A common characteristic is that the installed wind power capacity increased each year in each country. Thus, the impact of increasing wind power capacity on correlation can also be investigated. The total installed wind power capacity in the 10 selected countries increased by 22% over the 3 year period. It is important to note that, even though Table II reports the installed wind power capacity of the UK and the Republic of Ireland, for this study, datasets were available for GB, Northern Ireland and the Republic of Ireland separately. For the purpose of this analysis, GB comprises England, Wales and Scotland, and Ireland comprises of Northern Ireland and the Republic of Ireland reflecting the jurisdictions of the British Electricity Trading and Tariff Arrangement and the Single Electricity Market on the island of Ireland. Moreover, the datasets for GB are relative to a selection of monitored wind farms but not all wind farms installed in the country. Hence, the installed wind power capacity for GB used in the analysis is lower than the one reported in Table II, namely, 6953 MW by the end of 2012, 8179 MW by the end of 2013 and 8618 MW by the end of 2014.[47] In the case of Germany, all four TSOs declared to have projected the wind generation using reference sites in the control area and a calculation algorithm; therefore, the total installed capacity in the country is used for the normalization. For the other countries, datasets used are relative to the total installed wind power capacity.

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Table II. Wind power installed (MW) in Europe (EU-28) by end of year.[1,30–32] The 10 selected countries are highlighted in blue.

Country	2012	2013	2014
Austria (AT)	1377	1684	2089
Belgium (BE)	1375	1666	1959
Bulgaria (BG)	674	681	691
Croatia (HR)	180	261	347
Cyprus (CY)	147	147	147
Czech Republic (CZ)	260	268	282
Denmark (DK)	4162	4807	4882
Estonia (EE)	269	280	303
Finland (FI)	288	449	627
France (FR)	7623	8243	9285
Germany (DE)	30,989	34,250	39,128
Greece (GR)	1749	1866	1980
Hungary (HU)	329	330	329
Rep. of Ireland (ROI)	1749	2050	2262
Italy (IT)	8118	8558	8663
Latvia (LV)	60	62	62
Lithuania (LT)	263	279	280
Luxembourg (LU)	58	59	58
Malta (MA)	0	0	0
Netherlands (NL)	2391	2671	2865
Poland (PL)	2496	3390	3834
Portugal (PT)	4529	4730	4947
Romania (RO)	1905	2600	2953
Slovakia (SK)	3	3	3
Slovenia (SI)	0	2	3
Spain (ES)	22,784	22,959	23,025
Sweden (SE)	3582	4382	5425
United Kingdom (UK)	8649	10,711	12,633
TOTAL	106,009	117,388	129,062
Total study	84,690	93,667	103,019
% of TOTAL	79.89	79.79	79.82

The Energy Roadmap 2050 'sets out four main routes to a more sustainable, competitive and secure energy system in 2050: energy efficiency, renewable energy, nuclear energy, carbon capture and storage. It combined these routes in different ways to create and analyse seven possible scenarios for 2050'.[48] The aim of the 195 energy projects identified on the latest PCI list is to enable the single EU Energy Market and support the 'EUs energy policy objectives of affordable, secure and sustainable energy'.[49] Thus, it is important to establish any wind power correlation characteristics in an 'ideally interconnected Europe' to inform technical and policy decisions by key stakeholders. It has to be noted that this study does not model power system flows in the EU. In fact, no limits on power transport are imposed on this ideally interconnected power system. However, as the selected countries cover nearly 80% of the total installed capacity in Europe, the datasets used for this study can be considered quite representative of an ideally interconnected Europe.

3. METHODOLOGY

3.1. Normalized wind power

The wind power was normalized by installed capacity by comparing the datasets. Therefore, for each country, the normalized power was defined as

$$P_n = \frac{p_n}{C_I}, \tag{1}$$

where P_n is the normalized power production for hour n, p_n is the power (MW) produced for hour n and C_I is the installed capacity of the country. As mentioned in the previous section, in the case of GB, not all the operational wind farms installed in the country were available. Therefore, data are relative to a selection of wind farms and have been normalized using the installed capacity of the available wind farms only. The available installed wind power capacity datasets come from annual reports of the European Wind Energy Agency and are therefore yearly values. However, the installed wind power capacity varies during the year, and to take this into account, the datasets from December 2011,[50] 2012,[31] 2013[30] and 2014[1] have been interpolated to obtain quarterly values.

3.2. Cross-correlation calculation

Cross-correlation sequences were calculated for different time lags, m, in order to analyse the relationships between wind power generation of the EU country pairs. If each variable has N scalar observations, then the cross-correlation function is defined as

$$\rho_{i,j}(m) = \frac{1}{N-1} \sum_{t=0}^{N} \left(\frac{\overline{P_i(t) - \mu_i}}{\sigma_i} \right) \left(\frac{\overline{P_j(t-m) - \mu_j}}{\sigma_j} \right), \quad (2)$$

where μ_i and σ_i are the mean and standard deviation (SD) of the normalized power P_i respectively, and $i, j = 1, \ldots, 10$ are the indices for each country. It should be noted that the number of scalar observations, N, can vary from one time series to another as only the valid datasets were taken into account. Hence, the non-valid datasets were not counted in the calculation of the correlation. The analysis carried out in this study also used cross-correlation coefficients, which were obtained from (2) for $m = 0$. This calculation was made using the 3 years of datasets and also for each selected year separately. In addition to this, cross-correlation functions were calculated for time lags $|m| \leq 120$ h.

3.3. Statistical analysis

The statistical analysis was carried out by considering the hourly time series of each country. The mean, median and standard deviation values have been calculated together with the total number of hours in which instantaneous wind power is lower than 10% or higher than 75% of installed capacity for each country to characterize each data set. In addition to this, duration curves were created by counting the number of hours in each year that the wind power production exceeds a certain value of power (given as a percentage of the installed capacity). Wind power distributions for each country were also analysed. Finally, hour-to-hour variations were calculated by using normalized hourly wind power time series and computing the difference between each hour for each country.

3.4. Distance calculation

For each country, a weighted centroid has been defined to locate the 'centre' of all the installed wind power capacity of the country. The coordinates (X_C, Y_C) of the weighted centroid have been calculated considering the position of wind turbine aggregates in each country[51] and weighted by the number of wind turbines in that area and thus by the installed capacity. Therefore,

$$X_C = \frac{\sum_i x_i \cdot N_i}{\sum_i N_i}, \quad (3)$$

$$Y_C = \frac{\sum_i y_i \cdot N_i}{\sum_i N_i}, \quad (4)$$

where X_C and Y_C are the longitude and latitude of the weighted centroid C, x_i and y_i are the longitude and latitude of aggregated wind farms with total number of wind turbines N_i for that point.

Finally, the distances between each country were calculated using the coordinates of the weighted centroid. In the analysis, the wind power generation of each country was represented by a single time series associated to a single point in space, the weighted centroid. This weighted centroid approach represents the broad dependencies between each country, but the exact relationship will also be influenced by the size of the country. Note that although the correlation patterns will be affected by this aggregation, the patterns still provide useful information.

4. RESULTS AND ANALYSIS

4.1. Cross-correlation coefficients

The hourly time series of wind power generation from each country was used to calculate the cross-correlation coefficients of the country pairs. Figure 3 shows the overall correlation between each country pair as a function of their approximate distance, and the results are also provided in Table III for more clarity. The results have been calculated using all 3 years of

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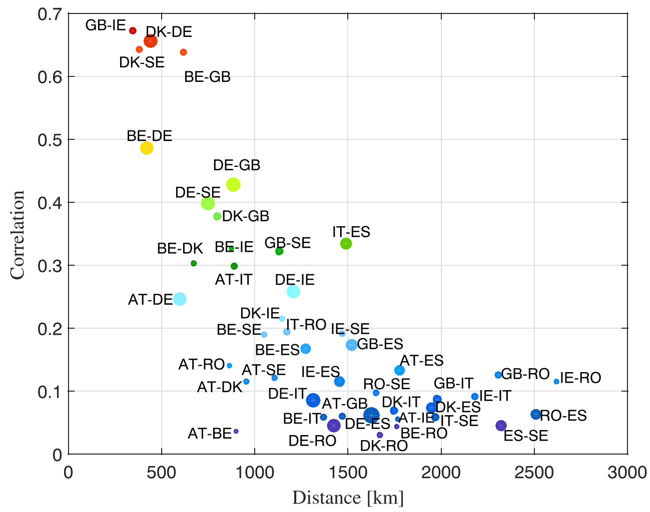

Figure 3. Correlation coefficients for country pairs as a function of the distance between them. The size of markers is proportional to the installed wind power capacity of each country pair. [Colour figure can be viewed at wileyonlinelibrary.com]

Table III. Correlation coefficients for country pairs calculated using all 3 years of data.

	AT	BE	DK	DE	GB	IE	IT	RO	ES	SE
AT	1	0.04	0.11	0.25	0.06	0.06	0.30	0.14	0.13	0.12
BE	0.04	1	0.30	0.49	0.64	0.33	0.06	0.04	0.17	0.19
DK	0.11	0.31	1	0.66	0.38	0.21	0.07	0.03	0.07	0.64
DE	0.25	0.49	0.65	1	0.43	0.26	0.08	0.04	0.06	0.40
GB	0.06	0.64	0.38	0.43	1	0.67	0.09	0.13	0.17	0.32
IE	0.06	0.31	0.21	0.26	0.66	1	0.09	0.12	0.12	0.19
IT	0.30	0.06	0.07	0.08	0.09	0.09	1	0.19	0.33	0.06
RO	0.14	0.04	0.03	0.04	0.12	0.11	0.19	1	0.06	0.10
ES	0.13	0.17	0.08	0.06	0.17	0.11	0.33	0.06	1	0.04
SE	0.12	0.19	0.64	0.40	0.32	0.18	0.06	0.10	0.04	1

data. The highest correlation of 0.67 as expected, because of their proximity, is between GB and Ireland. Denmark is highly correlated with Germany and Sweden with 0.65 and 0.64, respectively. In Figure 3, the size of the circle is proportional to the installed wind power capacity of the particular country pair.

This analysis was undertaken separately for each year to investigate changes in correlation from one year to another. Figure 4 shows a plot of the cross-correlation coefficients as a function of the distance between the country pairs with a best-fit curve. Three best-fit curves were plotted in order to better analyse changes from one year to another. The first curve (i.e. solid red line) considers only data from 2012, the second curve (i.e. dotted red line) considers only data from 2013 and the third curve (i.e. dashed red line) considers only data from 2014. The general model for the approximated curves is the exponential

$$f(x) = ae^{bx}, \tag{5}$$

where a and b are curve fitting parameters and x is the distance between countries in kilometres. The coefficients have been estimated using a least square approach, where a = 1.17, 1.36 and 1.05, and b = 0.0017, 0.0020 and 0.0014 for the datasets for 2012, 2013 and 2014, respectively. The results of the least squares approach in Figure 4 are compared with the results from Louie[6] using datasets from four North American TSOs (i.e. dashed yellow line) and Holttinen *et al.*[11] considering wind power production from several wind farms in the Nordic countries (i.e. dotted blue line). The Nordic analysis used datasets from single wind farms upscaled to a national scale. This is perhaps the reason for the lower values of correlation. This is illustrated in Figure 4 where the regression line is always lower than the other fitted curves. Louie[6] assigned this difference to wind power generation outputs from thousands of aggregated wind turbines, such that local transient conditions are filtered out. This forced an emphasis on larger spatio-temporal scales. Hence, national scale wind

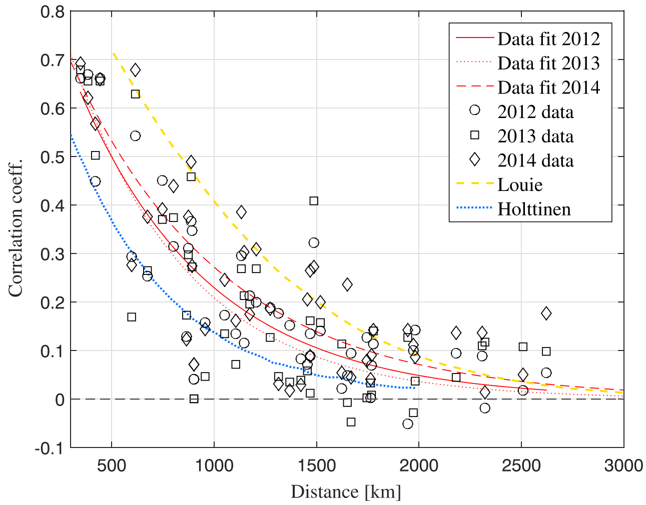

Figure 4. Correlation coefficients of country pairs versus distance with best-fit for 2012 data (solid red line), best-fit curve for 2013 data (dotted red line) and for 2014 data (dashed red line). The results are compared with the empirical relationship found in Louie[6] (dashed yellow line) and Holttinen *et al.*[11] (dotted blue line). [Colour figure can be viewed at wileyonlinelibrary.com]

power outputs are mainly affected by macro-scale conditions that tend to have higher correlation over longer distances than local effects that influence single wind farms.

Figure 4 also shows that cross-correlation coefficients change from year to year for each country pair. Considering the coefficients for each year, the highest correlation is between Ireland and GB ranging from 0.67 in 2012 to 0.69 in 2014. There are a few cases of negative correlation values for annual averages only, which are likely a result of small sample sets and low coefficient values. Several EU country-pairs exhibited near-zero correlation, in particular Italy–Sweden and Denmark–Romania. The value of the cross-correlation coefficients is influenced by many different factors. For example, the yearly changes shown in Figure 4 could be due to different weather conditions in each country, i.e. a year can be more windy than another in some places but not everywhere. Moreover, the correlation between two countries could vary because of changes in their installed wind power capacity. In addition to this, it is important to consider that the information on curtailment of wind farms was not available. Consequently, this affects the results, and it is not possible to distinguish if a change is due to curtailment or real variation in wind power production of a country.

4.2. Cross-correlation sequences

Cross-correlation sequences have been estimated according to (2) for lags $|m| < 120$ h (5 days). Figure 5 shows some examples of cross-correlation for three country pairs with high correlation (i.e. Ireland–GB, Denmark–Sweden and Germany–Denmark). The lag for maximum correlation is influenced by the direction of separation. For this reason, the graphs in Figure 5 were divided on a west–east axis and north–south axis considering the position of the weighted centroids for each country.

For the west–east axis, the position of the lag reflects the distance between the countries. For example, the weighted centroids for Ireland's and GB's are 347 km apart in the west–east direction, and the peak in correlation is between 5 and 8 h. This is due to weather fronts travelling from west to east. The time lag corresponding to the peak cross-correlation also changes slightly from one year to another. For example, in 2012, the time lag between Ireland and GB was roughly 5 h, whereas in 2014, it was 8 h. This increase in lag and the shift further east in the location of the weighted centroid could be due to the addition of wind power generation from large offshore wind farms in the North Sea in 2013 and 2014. In the case of the correlation function between Spain and Italy, a diurnal variation is evident with peaks at regular 24 h intervals. The main peak occurs at around $m = 24$ h, which could be due to the large distance of 1487 km between the weighted centroids and that a weather system hitting Spain could affect Italy the following day.

In the case of correlation along the north–south axis of the study area, the time lag for the peak of the cross-correlation is close to zero. This can be expected because these systems are located on a north–south axis from each other and experience weather fronts coming from the west almost at the same time. In fact, for Denmark and Germany, the highest correlation occurs with a 1 or 2 h lag. In the case of Denmark and Sweden, the separation direction is not aligned perfectly on a north–south axis. Therefore, the peak is slightly shifted with a time lag of around 5 h.

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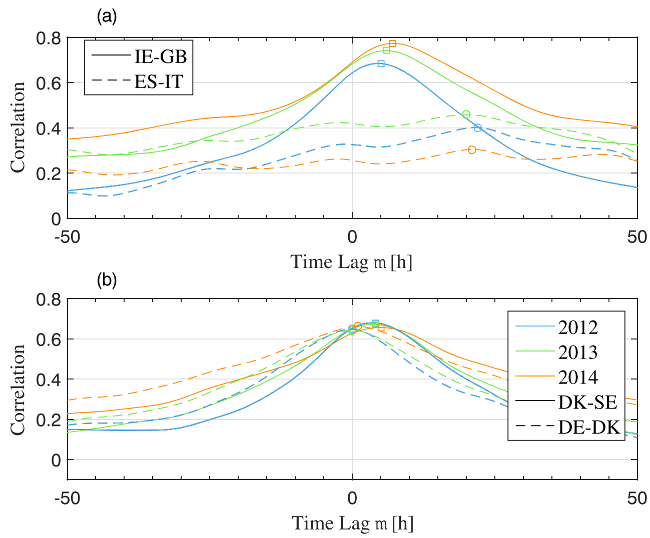

Figure 5. Cross-correlation functions with time shift applied to the second system listed in each pair, i.e. GB, IT, SE and DK time shifted respect to IE, ES, DK and DE, respectively. In (a) country pairs have a west–east direction of separation and north–south in (b). [Colour figure can be viewed at wileyonlinelibrary.com]

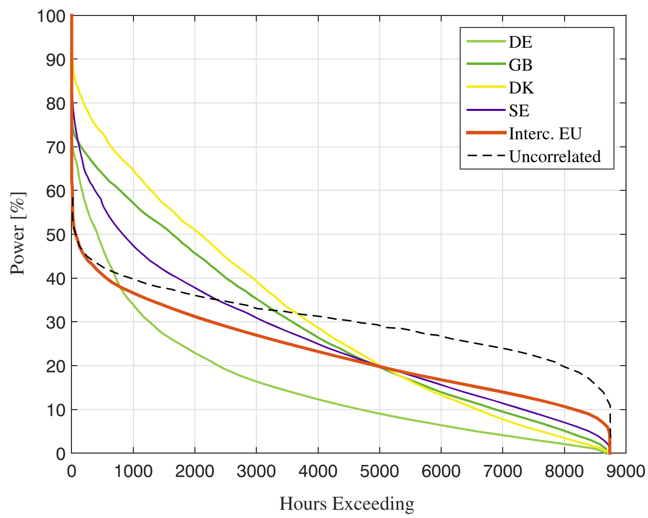

Figure 6. Duration curves for normalized wind power production in 2014 for four selected countries in the EU compared with the ideally interconnected Europe (solid red line) and an uncorrelated system simulation in Louie[6] (dashed black line). [Colour figure can be viewed at wileyonlinelibrary.com]

4.3. Aggregate wind power characteristics

For power systems operation, it is important to know the characteristics of aggregate wind power production over different time scales and its inter-temporal variations. Hence, yearly duration curves have been plotted to analyse the characteristics of each country's wind power production over 1 year. The duration curve has been calculated by counting the number of hours in 1 year that the wind power production exceeds a certain value of power, given as a percentage of the installed capacity. Figure 6 shows the duration curves for Germany, GB, Denmark and Sweden for 2014. The duration curves can be compared with the ideally interconnected European system (i.e. thick red line) and an uncorrelated reference system (i.e. dashed black line). The uncorrelated system was modelled by Louie[6] using a Monte Carlo simulation. The mode consisted of 20 uncorrelated wind farms of equal installed capacity, with an aggregate power output represented by a normal distribution with mean of 30% of the nominal installed power and standard deviation of 7.7%.

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The duration curves for the single countries are quite different from one another and reflect the different characteristics of each system. For example, the yearly duration curve for Denmark appears very asymmetric. It exhibits a larger number of high-production hours (i.e. $> 75\%$) compared with the other countries. This is evident by analyzing the results reported in Table IV. Germany has quite a significant number of low-production hours and very few hours of high-production hours as shown in Table IV. In fact, the duration curve for Germany starts with a sharp decrease as the number of hours of high power is smaller compared with the other countries. The curve then declines more slowly because of the high number of low-power production hours.

The shape of the yearly duration curve for the ideally interconnected European system is similar to the uncorrelated reference system, but the two curves do not coincide as the ideally interconnected European power system is shifted because of the different system characteristics. The mean is estimated to be around 21.5% of installed wind capacity, and the standard deviation is around 9%, whereas the uncorrelated system simulated by Louie[6] has a higher mean of 30% and a slightly lower standard deviation of 7.7%. In Table IV, it is shown that the number of wind power production hours below 10% of installed capacity in the ideally interconnected Europe is reduced by a factor of 2 compared with Sweden and up to a factor of 5.5 compared with Germany.

Table IV. Wind power output statistics.

Data set	Mean (%)	Median (%)	SD (%)	$\leq$ 10% (h)	$\geq$ 75% (h)
DK - 2012	29.0	24.0	22.0	2123	349
2013	27.7	21.5	22.1	2204	323
2014	30.7	25.3	23.3	2151	383
DE - 2012	17.3	12.8	14.8	3501	29
2013	16.3	11.5	14.6	3837	3
2014	15.8	11.1	14.6	3999	0
GB - 2012	22.2	18.4	16.1	2573	0
2013	27.5	24.5	17.8	1622	0
2014	28.5	24.0	19.6	1808	13
IE - 2012	27.0	23.1	19.4	2031	120
2013	28.3	23.4	21.3	2161	129
2014	27.4	21.2	21.7	2487	132
SE - 2012	25.1	22.5	15.4	1512	13
2013	27.8	23.8	17.1	1192	73
2014	26.2	22.9	16.3	1421	55
EU - 2012	21.6	20.8	8.6	633	0
2013	23.3	22.6	9.1	465	0
2014	23.3	21.9	10.1	595	0

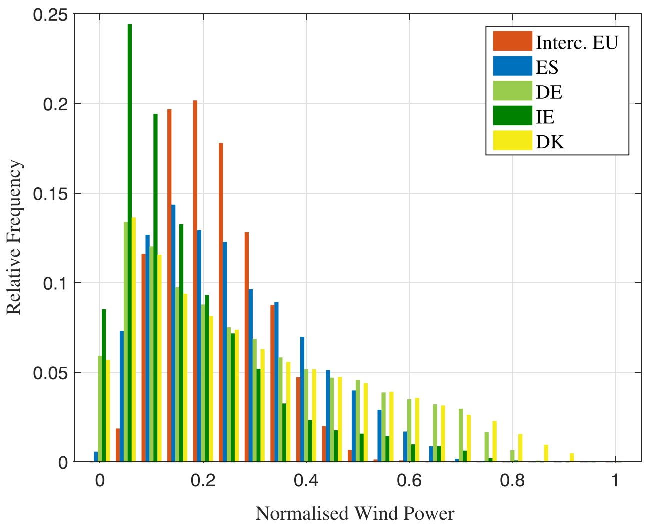

Figure 7. Wind power distribution for the ideally interconnected Europe (red), Spain (blue), Germany (light green), Ireland (dark green) and Denmark (yellow). [Colour figure can be viewed at wileyonlinelibrary.com]

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In this analysis, the duration of high and low wind power production has also been considered. The longest duration of low wind power production (i.e. < 10%) is 54 h for Romania, followed by 23 h for Germany, 17 h for Spain, 13 h for Belgium and 10 h for GB. The longest duration of peak wind power production (i.e. > 75%) is 41 h for Romania, closely followed by 40 h for Denmark and by 18, 16, 14 and 12 h for Sweden, Ireland, Austria and Germany, respectively. These results are important for power system operations and planning in an idealized interconnected Europe with regard to power flow, system stability, intermarket trading, storage and ancillary services as the countries with more advantageous correlation characteristics are highlighted.

The distribution of wind power production from each country has also been analysed. Figure 7 shows the distribution for Denmark, Ireland, Germany and Spain compared with the ideally interconnected Europe. It is evident that in general, the wind power distributions of these EU countries are spread over a wide range of values. However, wind power production in Spain has a distribution that is the closest to that of the ideally interconnected Europe with a wind power production that has a more concentrated distribution (i.e. a shorter tail).

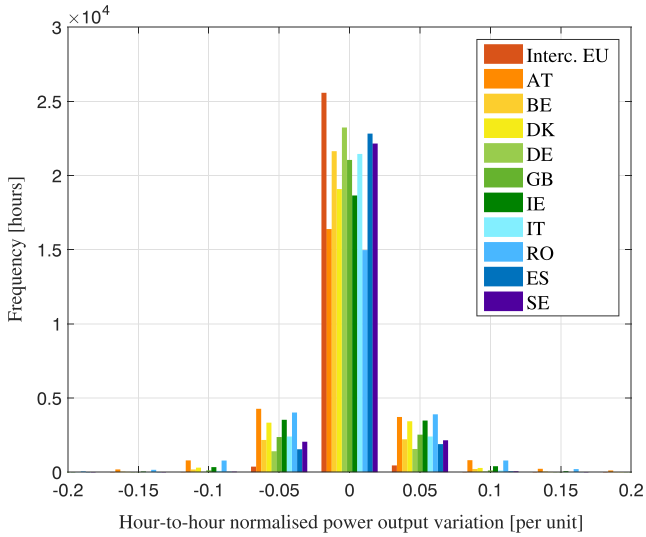

Figure 8. Histogram showing hourly variations of wind power outputs (normalized) from each country and the ideal interconnected European system. [Colour figure can be viewed at wileyonlinelibrary.com]

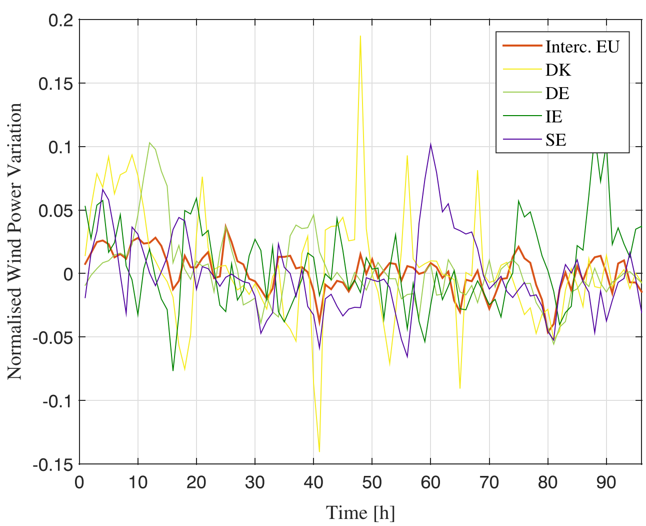

Figure 9. Hourly wind power variations as a fraction of installed wind capacity for the ideal interconnected European system (thick red line), Denmark (yellow), Germany (light green), Ireland (dark green) and Sweden (purple). [Colour figure can be viewed at wileyonlinelibrary.com]

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4.4. Inter-temporal variations

The inter-temporal variations of the wind power production from each country were examined to determine the frequency of occurrence of hourly variations. Hourly variations were calculated as an hour is the highest time resolution of the datasets. Figure 8 shows the frequency of occurrence of hourly power output variations for each country and the ideally interconnected Europe. The results of the analysis demonstrate that the ideally interconnected Europe has almost all hourly variations very close to zero, whereas the other countries exhibit larger hourly variations. Therefore, it can be inferred that the wind power production in the ideally interconnected Europe would have smaller hourly variations and a smoother wind power output. An example is reported in Figure 9 where 4 days (i.e. 96 h from 24 to 28 October 2013) of wind power production have been considered for Denmark, Germany, Ireland, Sweden and the interconnected Europe. During these dates, Denmark experienced a sharp increase in wind power production of almost 20% of installed wind power capacity (with a normalized wind power variation of 0.2) as can be seen by the spikes in the graph. However, at the same time, the wind power production in the ideally interconnected system increased by only 1.5% of the total EU installed wind power capacity. This indicates that there is opportunity for balancing in the ideally interconnected Europe. Overall, the maximum variation in wind power production in the ideally interconnected Europe was 3.6% of the total installed wind power capacity. Thus, in the ideally interconnected Europe, the inter-temporal variations are reduced and the resultant wind power output is smoother compared with that of the single countries. It is important to highlight that the benefits of large-scale smoothing effects are only possible if power exchange can be realized across countries.

5. CONCLUSION

This study analysed real wind power production data from 10 countries in Europe representing almost 80% of the total installed wind power capacity of the EU. The work focused on the following: (i) the correlation between the 10 countries related to distance; (ii) wind power production characteristics; and (iii) the inter-temporal variations in wind power production.

The analysis showed that the correlation between EU countries decreases exponentially with separation distance. This result is consistent with other studies.[6,11] This indicates that the PCI interconnectors between EU countries with low correlation should be prioritized in order to fully optimize wind power production and smooth wind power variability.[52] Moreover, the cross-correlation analysis found that the location of the peak in the cross-correlation function depends on both the separation and relative position of the country pairs with direction playing a key role. Peak correlation was observed at non-zero lag on a west–east axis, while the peak correlation was observed at close to zero lag along a north–south axis. This time lag could also be used for improving wind power forecasting (i.e. data from a particular country could be used to reduce prediction errors for another system taking into account their degree of correlation and especially the time lag between them) and thus mitigates the cost of wind power integration for TSOs. For example, this could be applied to develop a large-scale very-short-term wind power forecast model for all of Europe at the regional or even wind farm level using techniques like the sparse vector autoregressive model introduced by Cavalcante *et al*.[53] In addition, this time shift is important in many different aspects of power system operation and planning. The characteristics of the wind power production correlation between each country should be taken into account when planning and scheduling interconnector flows and grid operations because storage optimization and intermarket power trading and ancillary services will be influenced by the wind power correlation relationship of the two countries involved. Furthermore, another interesting finding often overlooked is that time lag can decrease and increase between countries depending on the geographic dispersion. For example, the lag increased by 3 hours and moved further east between Ireland and GB over 2012 to 2014. The change is perhaps due to wind power generation from large offshore wind farms in the North Sea over the same time period. This suggests that the lag value for maximum correlation and the location of the weighted centroid are altered as a function of the dispersion of wind farms in each country. This also has the potential to be critical in terms of PCI interconnector planning and operation. The highest correlation is between Ireland and GB (e.g. 0.67 in 2012 and 0.69 in 2014).

Furthermore, the analysis of the characteristics of wind power production showed that some countries have wind power production distributions with a large probability for low values and longer tails towards higher values. An ideally interconnected European system has been modelled to show that interconnections help to create a narrower and more symmetric distribution of wind power production, thus reducing periods of both very low and very high wind power generation. For example, in Table IV, it was shown that the number of wind power production hours below 10% of installed capacity in the ideally interconnected Europe is reduced by a factor of 2 compared with Sweden and up to a factor of 5.5 compared with Germany. This suggests that increased interconnection results in an overall ‘smoother’ system with a more concentrated distribution with characteristics similar to an uncorrelated system.

Thirdly, hourly wind power variations were analysed for each EU country and compared with the ideally interconnected Europe. The results showed that wind power variability is greatly reduced with interconnection, thus confirming the importance of the PCI projects in achieving the ‘EUs energy policy objectives of affordable, secure and sustainable energy’.[27] For

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example, it was also determined that the maximum variation in the wind power production for the ideally interconnected system was 3.6% of the total installed wind power capacity.

It is important to understand large-scale wind power production characteristics in an idealized interconnected Europe with the prospect of a single European energy target market in a future scenario with more and more renewable energy sources providing electricity and more interconnectors being built between EU Member States. The findings of this study indicate that an ideally interconnected Europe could mitigate the effects of increasing wind power and wind power variability. This in turn would result in more efficient power system operations because of increased grid stability, security and potentially less fluctuation in prices and improved predictability, thus reducing costs, emissions and primary energy consumption.

Finally, the analysis of wind power generation in 10 European countries has highlighted some important correlation characteristics that need further investigation, in particular, the lags in correlation between country pairs. These are especially relevant for power system operations, storage optimization and intermarket trading. This will form the basis of future research.

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