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How synchronous is wind energy production among European countries? ☆

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ABSTRACT

The amount of wind energy entering the European electricity transmission system is expected to increase in next decades. Indeed, Europe is on the path towards a deep transformation of its energy system, triggered in part by Directive 2009/28/EC (also known as the Renewable Energy Directive), in which wind energy will play an important role.

Europe is large enough to be impacted by multiple weather systems at any one time and as a consequence, absolute values and time patterns of wind power generation are different in each European country because of these non-homogeneous meteorological conditions. A future pan-European power transmission grid aiming to dispatch electricity production throughout the continent will thus have to face the challenge of balancing in real time differently intermittent and strongly inhomogeneous resources.

In this study, based on the wind fields provided at daily resolution for the period 1961–2050 by 12 regional climate models involved in the ENSEMBLES climate modelling intercomparison project, we have evaluated absolute national and European wind power production and its expected changes following the evolution of climate in Europe. Moreover, we have suggested a methodology to investigate in a quantitative way the complementarity among wind power patterns in different countries. Results show that the evolution of climate in Europe as projected by the ENSEMBLES participants, is not expected to have major impact on absolute wind energy production. Furthermore, the complementarity of wind energy patterns in different countries can be exploited by better integration of trans-boundary power exchange in Europe. For this reason, results are also discussed in the light of the design and dimensioning of the European electricity transmission system, with a special emphasis on the cross-border interconnections issues.

Contents

☆ The views expressed in this paper are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

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1. Introduction

Wind energy is at the core of the present and future European energy mix. According to the National Renewable Energy Action Plans, by 2020, the countries belonging to the European Union (EU) will have about 169 GW of on-shore wind capacity (see Table 1 for national capacities) installed which is expected to provide some 352 TWh of electricity, corresponding to about 10% of the expected electricity consumption of the EU for the same year [1].

Given this role of on-shore wind in the EU energy mix, present and future wind patterns should be studied in order to provide insights to energy system planners and policy makers regarding the availability and exploitability of wind resources in the next decades.

In this study, two main aspects have been investigated. Firstly we have evaluated the expected changes in absolute national and European wind power production, under the future climate projections for Europe produced by the ENSEMBLES project [2]. In this way we have been able to provide a quantitative vision of how climatic effects are expected to modify wind power production across Europe. Secondly, we have focused our attention on potential interactions between different European countries to complement national variations in wind energy production and we have developed and applied a methodology to evaluate the complementarity among wind power patterns in different countries and its role in achieving a well balanced European electricity transmission system.

1.1. Climatic driven wind power changes in Europe

The impact of climate change on wind patterns has been demonstrated, although not as relevant as for other meteorological variables, such as temperature. Indeed, future projections of wind fields at regional scale, derived from the dynamical and statistical downscaling of Global Climate Models (GCM), suggest only slight modifications in wind speed mean values and distribution [3–5].

Table 1
On shore wind capacity planned for 2020 in the EU.
Source: National Renewable Energy Action Plans.

Country	On-shore wind power – planned 2020 installed capacity (MW)
Belgium	2320
Bulgaria	1440
Czech Republic	573
Germany	35,750
Denmark	2621
Estonia	400
Ireland	4094
Greece	7200
Spain	35,000
France	19,000
Croatia	400
Italy	12,000
Cyprus	300
Latvia	236
Lithuania	500
Luxembourg	131
Hungary	750
Netherlands	6000
Austria	2578
Poland	5600
Portugal	6800
Romania	4000
Slovenia	106
Slovakia	350
Finland	1600
Sweden	4365
Total	**169,004**

Specifically, in Europe a slight increase of wind intensity is projected over northern Europe while a slight negative trend is expected over southern Europe [6].

In this study we have analysed in detail the climate-driven evolution of wind patterns and wind energy production in Europe. Such an analysis is not unknown in the scientific literature as, for instance, Tobin et al. [7] and Gaetani et al. [8], have used the same regional ENSEMBLES projections on which the present study is based, to evaluate the evolution of wind energy production in Europe in next decades. Nevertheless, by applying the Monte Carlo approach to capacity allocation developed in [9] to a continental scale, the results obtained in the present study have a wider validity and further confirm and generalize the results obtained in [7] regardless of the actual spatial deployment of wind power production capacity (see Section 3.2 for more details).

1.2. Complementarity of wind power production in Europe

The present study further aims to evaluate the complementarity of national wind power productions in Europe. For this purpose we have investigated the correlation (or the lack of correlation) between national wind energy production curves, on daily to yearly time scales. This analysis allows an assessment of the extent to which above average wind energy production in one area of Europe could be expected to sustain and/or complement shortfalls in production in other areas under a common EU electricity market, in both present and future climates, as described by ENSEMBLES projections.

Indeed, time complementarity among diverse dispersed intermitting energy resources, has been the subject of literature studies, generally showing that geographically dispersed wind (or PhotoVoltaic) generators are more likely to provide a smooth collective supply profile because of random cancellation of the variations, this effect is particularly evident in the case of wind power.

For instance Widen [10] analyses large-scale solar and wind power for Sweden, using climatic data covering 8 years with an hourly resolution and finds that solar and wind power are generally negatively correlated on all time scales, from hourly to annual, but that the correlation is strongest for monthly totals. Consequently, a balanced combination of solar and wind power can reduce total variations. Similar studies have involved various other geographical areas and time scales [11–13].

Wind is a variable and partly unpredictable energy source and even if general seasonal cycles can be observed, the precise time profile of wind power generated is inevitably different in different countries, depending on local weather patterns and turbines locations [14]. Such diversity could be both an opportunity and an issue for the EU energy system as a whole: if peaks and troughs in wind flows are synchronous throughout the main wind power production areas, overall EU energy production will be formed of high peaks alternating with low troughs. Conversely, if high peaks in some production areas are synchronous with troughs in other areas, the different intermittency phases complement each other and the overall production will be smoother, provided that sufficient transmission capacity is available to allow national production to balance one another.

In this second case, the European electricity market as a whole will benefit from a more stable and predictable amount of power available from wind sources, with an overall smaller need for energy storage and with a lower risk of energy curtailment needs (see also the appendix of Monforti et al. [9] for a quantitative discussion of these concepts).

Until now, the temporal complementarity of wind patterns have been studied in just a few regions of the world. For instance, Santos-Alamillos et al. [15] have analysed the potential contribution of wind energy to the baseload within the Iberian Peninsula using a method based on principal component analysis (PCA). In this way, spatiotemporal balancing of wind energy resources is investigated in order to assess optimal wind farm locations in order to reduce power fluctuations.

Similarly, Liu et al. [16] investigated wind energy complementarity across China, demonstrating that whereas a combination of wind and solar resources over a given area reduces the occurrence of zero-power hours, wind resources alone are sufficient to provide baseline power production, if a large enough area is considered.

In this study we have analysed for the first time the time complementarity of wind patterns and potential wind power production on the whole European continent. As our investigation was based on decades-long daily time series from ENSEMBLES, results are robust enough to be of interest for energy system modellers and planners, in particular in designing appropriate cross-border transmission capacity.

1.3. Wind energy integration in the European power system and cross-border transmission capacity

Several literature studies have assessed the consequences of integrating variable energy sources into the European electricity system. For instance, Widén et al. [17] summarized the state of knowledge on the time scales of variability of Renewable Energy Sources (RES hereafter) – including also tidal and wave power in a future perspective, on both European and global domains, while in [18] authors applied a market stochastic model in order to assess the future deployment of RES up to 2050 following different techno-economic scenarios. This last study confirmed the crucial role of transmission capacity in reaching a successful technical and economic integration of the electricity market, to cope efficiently with RES time variability. Indeed, an efficient cost optimization was shown to be possible only by increasing total trans-boundary power transmission, regardless of the scenario studied. In [19] authors also assessed the economic benefits of transmission capacity, showing how additional cross-border transmission capacity between 2010 and 2025 is expected to reduce annual dispatch costs. In the same paper, the trade-off between cross border transmission capacity and energy storage was also investigated, showing that scenarios providing higher transmission capacity result in both a reduced need for storage and reduced wind and solar energy curtailment.

In conclusion, once intermittent RES are fed into a homogeneous European grid, the beneficial effect of averaging different intermittency patterns, partially complementing each other, into a smoother production profile has been demonstrated from both the technical and economic point of view. For this reason, the detailed knowledge of the typical potential wind power supply time profiles for each EU country and their complementarity, offered by our study is crucial for a proper assessment of present and future electricity transmission flows across the European grid and inform its proper dimensioning, including setting consistent cross-border lines.

1.4. Summary of the paper

In summary, Section 2 presents the methodology and data sources: data sets from the ENSEMBLE project are briefly presented in Section 2.1 while in Section 2.2 the methodology used for assessing wind power production at the country level is introduced. Section 2.3 introduces the indicators used to evaluate wind power profiles complementarity at the country-to-country and country-to-EU level and the synchronicity indicator to be applied to the whole EU area. Section 3 shows results obtained for Wind Power Density (WPD) analysis and potential wind energy production by country (Section 3.1) and in the EU (Section 3.2). Results of the complementarity studies are discussed in Section 3.3 while in Section 4 results are summarized and their implications for the future dimensioning of the European power system discussed. Appendix A provides a detailed quantitative evaluation of actual climate impact on both wind power potential and spatial wind complementarity in the EU while Appendix B investigates the relation between complementarity and modelling scale.

2. Materials and methods

2.1. The ENSEMBLES project

The ENSEMBLES project, funded under the European Commission's Sixth Framework Programme from 2004 to 2009, aimed to provide probabilistic estimates of climatic risk through climate model simulations. The project developed an ensemble climate forecast system to construct integrated projections of future climate change across a range of time (seasonal, decadal and multidecadal) and spatial scales (global, regional and local) [2].

The ENSEMBLES 21st century simulations have been set up following the recommendations made by the IPCC for the AR4 [20], to assess different sources of uncertainty in climate change projections. An ensemble of different climate models, a so-called multi-model ensemble, is used to sample uncertainties in model formulation and isolate model errors [21]. Moreover, three different emission scenarios, namely SRES A2, A1B and B1 [22], each following different storylines for the economic and cultural development of the world, are used to sample possible developments of greenhouse gases (GHG) emissions in the future. A set of high-resolution climate change projections has been made by state-of-the-art global and regional climate models (GCM and RCM, respectively). RCM are used for the dynamical downscaling [23] of the GCM outputs to a finer resolution over Europe.

RCM climate simulations use the A1B scenario for GHG concentration, and cover the period 1950–2050 (some of them reach 2100), on a common domain over Europe (from South Mediterranean coast to Cape North), at 25 km horizontal resolution. The A1B scenario assumes a world of very rapid economic growth, with a global population peak in mid-century. In this study the climate evolution from 1961 to 2050, simulated by 12 RCM, is analysed. Details on RCM and their driving GCM are summarized in Table 2.

In the ENSEMBLES datasets, wind data are available with daily resolution at 10 m height all along the simulations time spans. ENSEMBLES wind data are known to be biased when compared with observations [7] but methodologies for bias corrections for wind data usually require quite a large amount of work and are at the moment much less robust than for temperature and precipitation. Moreover, the scope of this study is not the precise assessment of the absolute values of point-by-point wind potential, but the investigation of the main features of its temporal and spatial patterns and how wind power patterns are expected to respond to climatic signals. Thus the raw data have not been corrected and analysis has been focussed on relative changes rather than on absolute values.

Wind pattern evolution and the related WPD changes in ENSEMBLES projections have been analysed by Tobin et al. [7] and Gaetani et al. [8] and results will be reported whenever relevant for the power potential production evaluation.

Table 2
Institutions participating to the ENSEMBLES project, regional climate models and driving global models. Short names have been used in figures.

Institution	RCM	Driving GCM	Short name
Community Climate Change Consortium for Ireland (C4I)	RCA3	HadCM3	RC3_HAD
Meteo France, Centre National de Recherches Meteorologiques (CNRM)	RM5.1	ARPEGE	RM5_ARP
Danish Meteorological Institute (DMI)	HIRHAM5	ARPEGE ECHAM5 BCM	HIR_ARP HIR_ECH HIR_BCM
Swiss Federal Institute of Technology Zurich (ETHZ)	CLM	HadCM3	CLM_HAD
Royal Netherlands Meteorological Institute (KNMI)	RACMO2	ECHAM5	RAC_ECH
Met-Office, Hadley Centre for Climate Prediction and Research (METO-HC)	HadRM3	HadCM3	HAD_HAD
Max-Planck Institut für Meteorologie (MPI-M)	REMO	ECHAM5	REM_ECH
Swedish Meteorological and Hydrological Institute (SMHI)	RCA	BCM ECHAM5 HadCM3	RCA_BCM RCA_ECH RCA_HAD

2.2. Wind power production in Europe – a country based analysis

The wind power potential production in European countries, as seen by the ENSEMBLES models, was assessed following a two-step process: in the first step the theoretical loading factor for a reference wind turbine was calculated for each model in each grid of the domain, while in the second step power production from the whole country was obtained, given the projected geographical distribution of turbines.

2.2.1. Capacity factors

Theoretical capacity factors[2] based on ENSEMBLES daily 10 m winds were computed by means of the following procedure:

1. $w_{10}(x,y)$ daily wind speed data at 10 m height in the (x,y) location were extrapolated to 80 m on the basis of the logarithmic profile

$$w_{80}(x,y) = w_{10}(x,y) * \log(80/r(x,y))/\log(10/r(x,y)) \quad (1)$$

with $r(x,y)$ being the roughness length in (x,y) as given by KNMI model data in metres. As in some cases this extrapolation method has been shown to result into unrealistic excessively high wind speed values, an alternative approach was also developed based on the ECMWF operational analyses fields. The a and b coefficients for the linear relationship

$$w_{80}(x,y) = a(x,y) * w_{10}(x,y) + b(x,y) \quad (2)$$

were best-fitted on the basis of 10 years (2002–2011) of ECMWF analyses model fields for wind speeds at 10 m and 80 m heights, regridded to the KNMI standard grid and used to extrapolate ENSEMBLES wind speeds from 10 m to 80 m height.

For each (x,y) location the daily average wind speed at 80m height $w_{80}(x,y)$ was then defined as the minimum between its two estimates obtained through formulas (1) and (2).

[2] According to IEA [24] the *capacity factor* is the measure of the productivity of a wind plant. i.e., the amount of energy the plant produces over a set time period (one year in the present study), divided by the amount of energy that would have been produced if the plant had been running at the full nominal capacity during that same time interval.

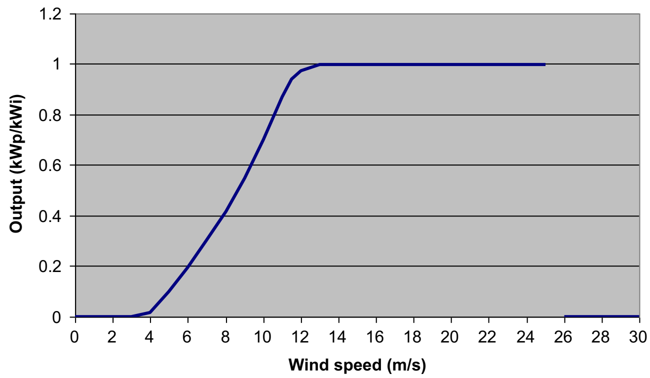

Fig. 1. Power produced per power installed in Vesta 90 generator as a function of the wind speed (adapted from [27]).

2. Given $w_{80}(x,y)$, 24 hourly values for wind speed were randomly generated following a Weibull distribution with mean equal to $w_{80}(x,y)$ and a shape factor equal to 2 [25,26]. Hourly wind speed data were then used to estimate the hourly wind power production per MW installed (normalized power production) by means of the wind-power curve shown in Fig. 1, reproducing the power production curve of a typical wind turbine available on the European market (namely Vesta V90).

Hourly production values were then summed over the day to obtain 32,850 (or 32,400)[3] daily production over 90 years and along each year to obtain 90 (1961–2050) values of annual theoretical capacity factors at each grid point for each of the 12 model runs. Additional capacity decreasing factors such as actual availability or power losses were not included in the present theoretical analysis.

2.2.2. Countries power production: A Monte Carlo assessment

Once theoretical loading factors are computed, the actual power production in a given country depends on the location of installed turbines and their capacity [28]. Details of turbines installed in European are at least partially available from several commercial and open source databases (see again [28] for a summary) each offering different data quality as far as key parameters such as coverage, updating frequency and spatial resolution are concerned. The spatial allocation of future wind turbines on the other hand, is difficult to forecast, as the localization process is dependent on social as well as economic and practical aspects, and are thus generally difficult to investigate.

Studies exist that have evaluated the possible spatial evolution of the European wind power park in next years [28,7] based on power production optimization, cost minimization and practical geographical constraints leading to the identification of most suitable areas. Nevertheless, given the coarse resolution of the ENSEMBLES reference grid (about 25 km), in practice a detailed geographical analysis is difficult. For this reason, a more pragmatic approach to modelling the actual and future location of wind turbines was taken in this study, based on partially random allocation: the on-shore wind installed capacity planned for 2020 (see Table 1) in 27 of the EU-28 countries, with the exclusion of Malta,[4] was divided into parcels of 20 MW, roughly representing groups of about 10 wind turbines i.e., a small sized wind farm. Each 20 MW capacity parcel was then randomly allocated in the country territory, subject to the only constraint of the load factor in each selected (x,y) location being larger than the average load factor of the country itself. In this way, capacity is randomly allocated in "promising" areas, consistently defined by each model as providing an "above the average" potential for the 90-year time period spanned by the study.

As an example, Fig. 2 shows the actual capacity distribution in EU-28 in the case of three models (rows) and for three different capacity random allocations (columns). Comparing rows in Fig. 2 shows how the three models provide quite a different pattern of promising wind production areas: see e.g., the Great Britain, with RM5_ARP focussing on the Southeast with some spots in Scotland, RAC_ECH suggesting the central section and a more southern strip and RCA_ECH suggesting a much larger area all along the country. Being the criteria for selecting "promising" areas homogeneous among the models, these differences in allocation patterns are related to intrinsic differences in wind patterns as forecasted by the different models.

On the contrary, the comparison of different figures in the same rows on Fig. 2 shows how the random allocation procedure used here provides different patterns of installed capacity. Capacity allocation patterns in countries with higher capacity density tend to be more uniform than in countries with lower installed capacity. Indeed, the more capacity is installed, the more geographically different locations are expected to be exploited and the more uniformly and sparsely wind turbines are expected to be distributed on the territory, subject to the availability of a minimum potential.

In effect, the slightly constrained random allocation procedure applied here has allowed the investigation of several "worlds" in which each country allocates its wind turbines chasing for above-the-average productive areas, where these wind-rich areas are consistently defined through present and future meteo-climatic features, being different for each climate model considered.

Once the capacity has been allocated on the territory, daily (annual) wind power production for each country can be computed simply multiplying the installed capacity in each grid point of the country times the daily (annual) capacity factor as defined in Section 2.2.1.[5] The capacity allocation procedure has been repeated ten times for each model in order to evaluate the variability arising from the overall capacity being differently split on to the territory.

Results and further elaborations are reported in Sections 3.1 and 3.2.

2.3. Complementarity of wind power potentials in the European Union and its member countries

Daily wind production profiles obtained following the methodology detailed in Section 2.2 were compared in order to assess time correlation of wind production for the EU countries and for the EU as a whole.

2.3.1. Country-to-country complementarity

Pearson's correlation coefficient between countries wind power production is the key quantitative parameter used in this study for assessing national production complementarity. For each couple of countries i and j the yearly correlation coefficients $R^{y}_{i,j}$

[3] Four ENSEMBLES models run on 360-day years while other eight models run on 365-day years. Yearly results in Section 3 have been renormalized to allow comparison. Leap years are not considered in models runs.

[4] Malta exclusion followed the observation that, being the total surface of its islands approximately 50% of a single model grid, it is invisible to the ENSEMBLES data. Wind installed capacity in Malta is expected to reach 15 MW in 2020.

[5] It is worth emphasizing that the capacity allocation patterns do not change along the simulation years, as the present study focuses on climate evolution and not on the evolution of installed wind power fleets. For this reasons expressions such as "Wind Power production in 2050" have to be read as "Wind Power that would be produced in the meteorological year 2050 by the 2020 wind turbine fleet"

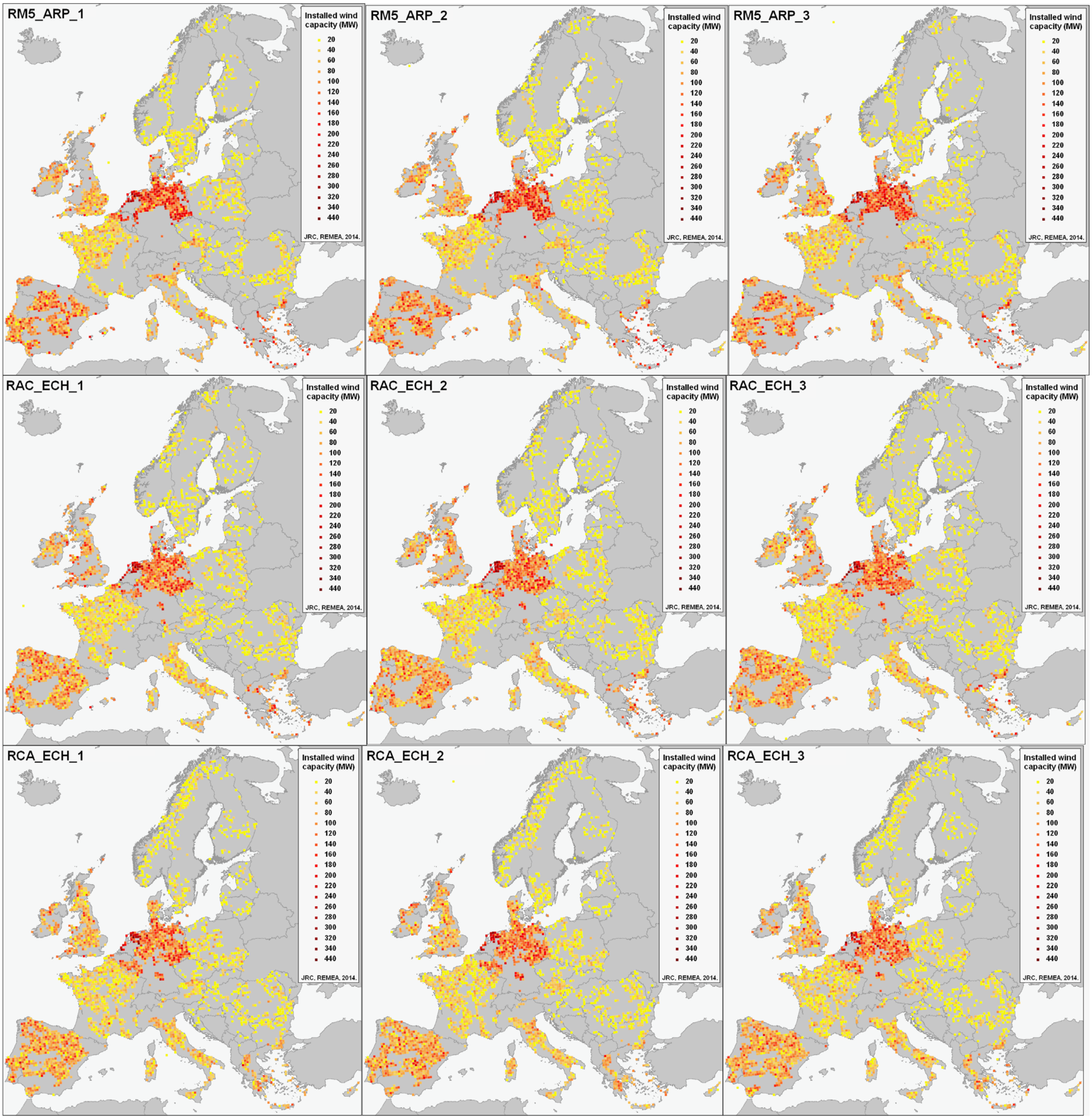

Fig. 2. Allocation of wind capacity planned for 2020 in EU-28 for three models (RM5_ARP– top row, RAC_ECH middle row, RCA_ECH – bottom row) and for three different random allocations (columns).

were computed as

$$R^{y}_{i,j} = \frac{\sigma^{Y}_{i,j}}{\sqrt{\sigma^{Y}_{i} \cdot \sigma^{Y}_{j}}} \tag{3}$$

where

$$\sigma^{Y}_{i,j} = \sum_{d=1}^{Nd} \left(W^{Y}_{i}(d) - \overline{W}^{Y}_{i} \right) \left(W^{Y}_{j}(d) - \overline{W}^{Y}_{j} \right) \tag{4}$$

$$\sigma^{Y}_{i} = \sum_{d=1}^{Nd} \left(W^{Y}_{i}(d) - \overline{W}^{Y}_{i} \right)^{2} \tag{5}$$

$$\sigma^{Y}_{j} = \sum_{d=1}^{Nd} \left(W^{Y}_{j}(d) - \overline{W}^{Y}_{j} \right)^{2} \tag{6}$$

where Y is the year, ranging from 1961 to 2050, $W_i{}^{Y}(d)$ is the wind energy production in the ith country in the dth day of year Y, $\overline{W}^{Y}_{i}$ is the yearly average of wind power production in the ith country in year Y, and N_d equals either 360 or 365 depending on the model considered (see footnote 4). Coefficients were computed for each of the N capacity allocations and for each of the 12 ENSEMBLES projections available, looking mainly for the actual influence of capacity allocation and the presence of a climate signal. Results are presented and discussed in Section 3.3.1.

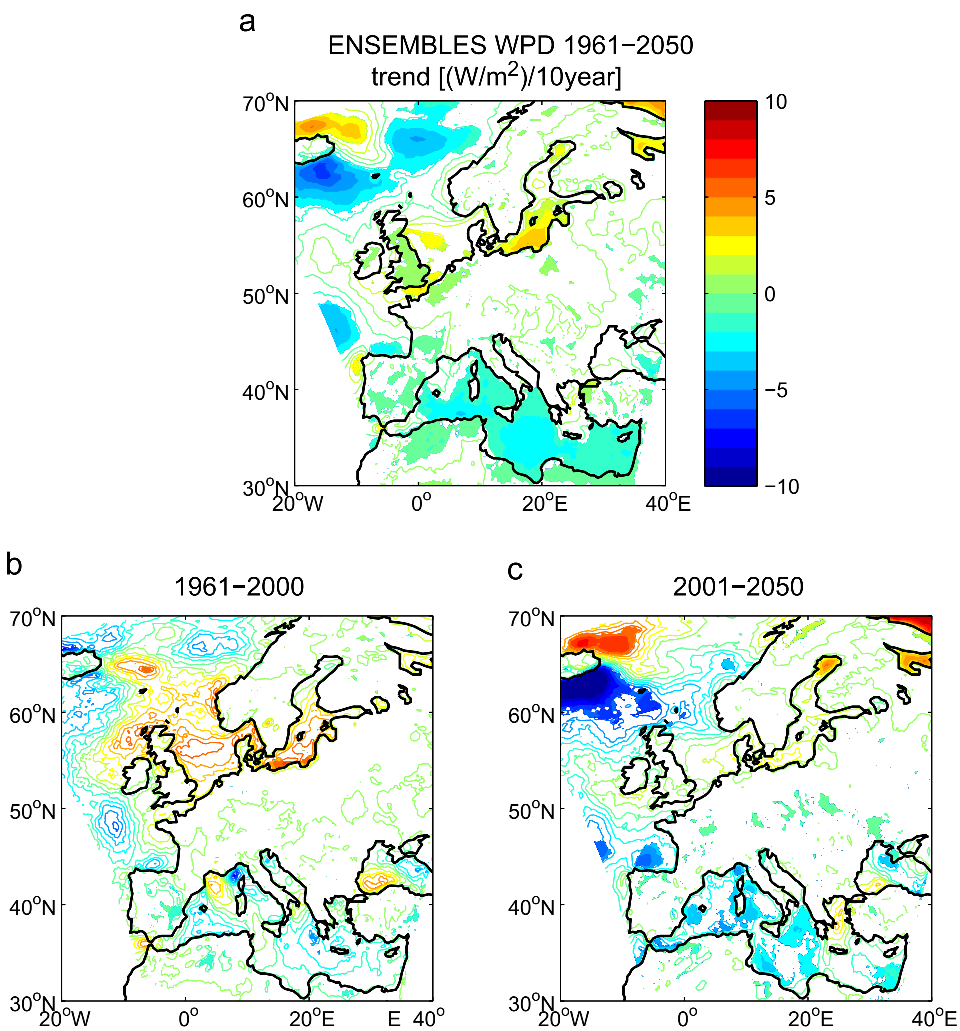

Fig. 3. Wind Power Density (WPD) trends [(W/m^2)/10-year] in ENSEMBLES RCM simulations (ensemble mean): (a) 1961–2050, (b) 1961–2000, and (c) 2001–2050. Shadings indicate 95% significant trends, measured by a Mann–Kendall test.

2.3.2. Country-to-Europe complementarity

While the $R^{Y}_{i,j}$ correlation coefficient describes the complementarity of wind power production among pairs of countries, it is interesting to assess the wind power complementarity between a single country and the rest of the EU in order to understand to what extent wind power produced in each single country is synchronous with the overall EU wind production.

To this aim, the indicator $R^{Y}_{i,EU}$ has been computed as the average of $R^{Y}_{i,j}$ (for $i \neq j$) weighted with the installed capacity in each country, i.e.,

$$R^{Y}_{i,EU} = \sum_{j \neq i} C_j R^{Y}_{i,j} / \sum_{j \neq i} C_j \tag{7}$$

where the weighting procedure has been introduced for the dual purpose of obtaining an indicator ranging between -1 and 1, and to take into consideration differences between high and low production countries. High values of $R^{Y}_{i,EU}$ indicate that wind energy produced in *i*th country is synchronous with production of countries in the rest of EU, while lower values indicate an higher complementarity between wind energy production in the *i*th country and the rest of EU. Such a number could be of interest both for the *i*th country, when planning to exchange wind power production on an EU market without a specific partner defined and for the rest of Europe in order to evaluate how much "diversity" in wind power patterns the *i*th country adds to the common pool. Results are shown and discussed in Section 3.3.2.

Table 3
Wind Power Classes definition.

Class	WPD [W/m^2]	Resource potential
1	<100	Not suitable
2	100–150	Marginal
3	150–200	Fair
4	200–250	Good
5	250–300	Excellent
6	300–400	Outstanding
7	>400	Superb

2.3.3. European wind power production synchronicity

Finally, a single indicator providing a measure of the "synchronicity" of wind power production in the EU was computed as the average of the country-to-Europe correlation indicators again weighted through the installed capacity in each country:

$$S^{Y} = \sum_{i} C_i R^{Y}_{i,EU} / \sum_{i} C_i \tag{8}$$

where *S* is an overall measure of the synchronicity of wind power productions and it is dependent on weather patterns across the entire EU. Again ranging between -1 and 1 by definition, high values of *S* correspond to wind fields varying in time with similar patterns and leading to similar wind power patterns in all countries, while lower values of *S* indicate the coexistence of different weather regimes and time scales and consequently more diverse and less time correlated wind power production patterns in different countries. Results obtained for the synchronicity indicator in Europe will be shown and discussed in Section 3.3.3.

3. Results

3.1. On-shore wind power production in Europe and its climate evolution

3.1.1. Wind patterns and wind power production in the EU

The analysis of the ENSEMBLES wind fields, the physical precursors of wind power production, did identify major impacts from the climate evolution. A detailed analysis of climate related wind patterns changes in Europe is available in [8] and here just the main results on WPD) [29] and associated wind power classes are summarized.

WPD is defined as

$$WPD = 1/2 * \rho * w^3,$$

with ρ being the air density ($\rho = 1.225 - 1.194 * 10^{-4} * z$, at elevation z), and w being the wind speed. *WPD* is computed considering the operational range of wind turbines in the 2–4 MW class (e.g. Vestas V-90), which is 4–25 m/s at the turbine hub-height, and 3–19 m/s at 10-m height [3].

The WPD trends (Fig. 3) generally show stability in the 1961–2050 period in the Continental Europe, with exceptions in some areas: WPD decreases offshore in the Mediterranean Sea (with a decrease of about 30 W/m^2) and the North Sea (showing a decrease of around 80 W/m^2), while an increase is observed in the Baltic Sea (increasing by up to 40 W/m^2) and the British Isles (increasing by up to 10 W/m^2), with an acceleration of the changes in the present-to-future time range (bottom panels).

The suitability of a certain area for wind power exploitation is usually described by means of the associated Wind Power Class (WPC – see Table 3) ranking, based on WPD values. Class 3 or greater are suitable for most wind turbine applications, whereas Class 2 is marginal and Class 1 is generally not suitable [30].

The modifications in WPC between future (2031–2050) and present (1991–2010) climate conditions are presented in Fig. 4. It results that most of the changes are observed offshore, while the differences inland are limited and sparse, and almost all the observed modifications are limited to one class.

The spatial pattern of potential wind energy sites is thus largely unaffected by climate change as found by Tobin et al. [7] and, as expected, the climate stability of actual wind patterns on the European continent leads to climatically stable wind power production in the EU countries.

National wind power production was estimated for each day of the simulated period and for each model as described in Section 2.2.2, repeated $N = 10$ times the random allocation of installed capacity and then analysed to assess statistically significant differences among the different datasets.

Even if ANalysis Of Variance (ANOVA) tests have shown that daily wind production sequences are indeed statistically different in different simulated years for all models and countries considered, the annual wind energy production did not show evidence of strong climatic effects for most of the countries and models considered, in full agreement with the general picture of small changes into physical potentials. More details on numerical tests performed and their results are presented in Appendix A.

3.1.2. The impact of the actual deployment of installed capacity

The next group of tests was aimed at assessing the differences in national wind power production rooted into the different capacity allocation patterns tested. For this purpose, the 10-member groups of 90-year long sequences of daily wind power produced by the 12 investigated models in each European country were subjected to an ANOVA analysis in order to verify their similarity. Overall, the results show the influence of the total amount of deployed capacity, with countries with a smaller installed capacity being more likely to show significant differences in power production related to actual spatial deployment of turbines.

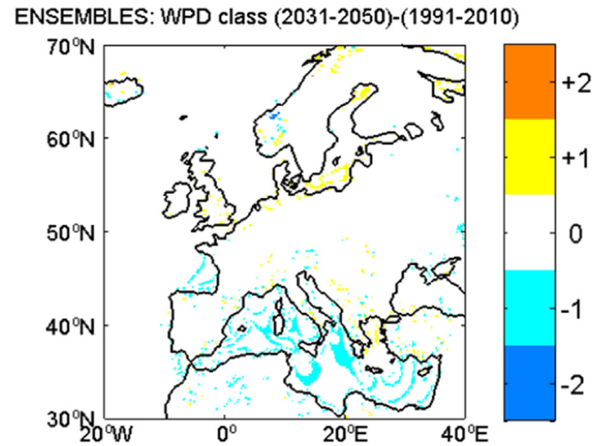

Fig. 4. WPC changes in ENSEMBLES RCM simulations (ensemble mean) between 1991–2010 and 2030–2050 periods.

In comparison, in the case of countries deploying larger capacities, ANOVA was not able to demonstrate significant differences arising from the different random spatial allocations of the installed capacity. Nevertheless, even when differences were found to be statistically significant, they were generally small or very small in absolute values and did not affect the main features of time profiles.

As an example Fig. 5 shows the wind power daily production in a given year as estimated by RAC_ECH model in Slovenia (the country with the smallest installed capacity among the ones analysed) in 4 different hypotheses of 2020 installed capacity deployment. In the case illustrated, profiles were indeed found to be statistically different by ANOVA, but a visual analysis shows how general patterns remain very close to each other even in this case.

For this reason, a first main finding of the present study consisted in demonstrating through a Monte Carlo analysis that *the actual deployment of national wind turbine fleets in 2020 in a country is expected to have a little overall influence on the main features of the national wind power profiles*, provided that the basic assumption of wind turbines being installed in areas with above average wind power potential is respected.

Following this result, the variability among different capacity deployments has been generally neglected in subsequent analyses and the average values of the analysed variables among the $N = 10$ capacity deployment scenarios are considered.

3.1.3. Model dependence

Inter-model wind power profile variability is on the contrary very strong, as is to be expected considering the independence between model runs, ensured by the diverse mixture of RCMs and driving GCMs and the absence of any post-processing applied to force models towards common results. Again as an example, Fig. 6 shows daily wind power production in 2000 as estimated by 3 different models (namely RAC_ECH, RM5_ARP and CLM_HAD) in France.

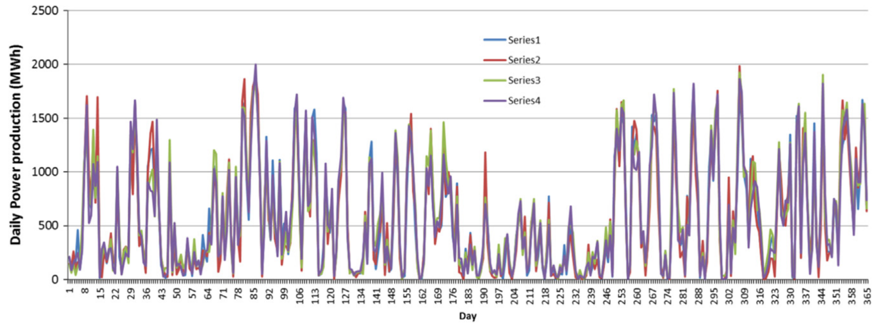

Fig. 5. Wind power daily production foreseen by the RAC_ECH model in Slovenia in a reference year in 4 different deployment hypotheses of 2020 installed capacity deployment (MWh).

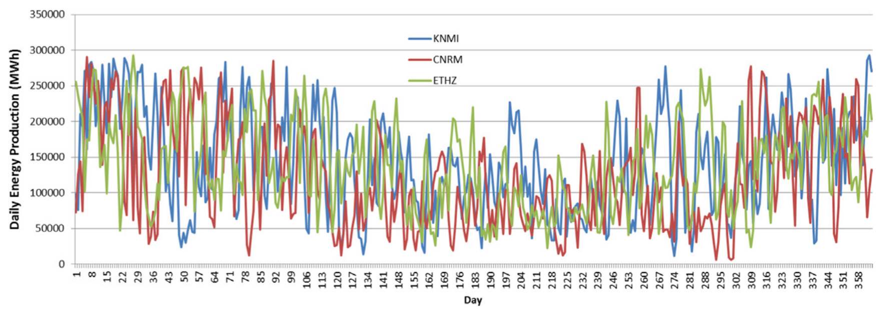

Fig. 6. Wind power daily production (MWh) in 2000 as estimated by 3 different models (namely RAC_ECH – blue, RM5_ARP – red- and CLM_HAD – green) in France. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

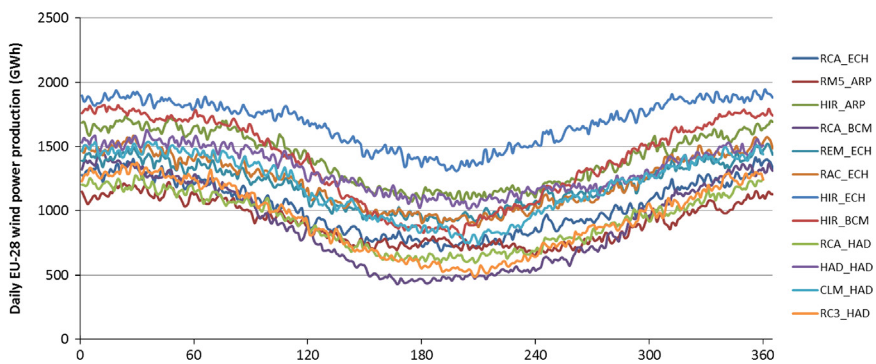

Fig. 7. Wind power production in EU-28 (GWh/day) in the average year for the 12 ENSEMBLES models.

It is evident how, even if some common features are visible such as a lower production in summer than in winter, the three models behave radically differently day by day, with such a diversity being statistically significant even in the case of all other countries and models included in the study. However, this aspect should not be regarded as a limitation, because combination of inter-model differences into the ensemble mean demonstrates the capability of reproducing a reliable estimate of climate variability [31].

3.2. On-shore wind power production in Europe: The overall picture

Overall wind power production for EU-28 was evaluated simply summing up countries production for each day of the simulation, obtaining $N=10$ sequences of 90-year long daily generated on-shore EU-28 wind power for each of the 12 models studied. ANOVA analysis has again shown no siginificant differences in EU-28 power production profiles arising from differences in the actual allocation of turbines and the $N=10$ EU-28 production profiles are very close to each other. Thus, as is the case for EU-28 WE production, the variability arising from different capacity deployments scenarios has been neglected and the average values among the $N=10$ realizations are generally considered.

On the contrary, ANOVA has shown that yearly EU-28 wind power profiles differ statistically from each other, but, consistent with findings in Section 3.1, the annual EU-28 wind energy production has shown very little evidence of climatic related changes. More details on numerical tests performed and their results are also presented in Appendix A.

Even in the case of the cumulated EU-28 wind power production, different models have provided quite different estimates. Fig. 7 show wind power production in EU-28 estimated by the 12 models for the average year[6] demonstrating both the differences among models and the clear wind power seasonality effect common to all models.

Tables 4 and 5 report the average of all daily wind power production values (in GWh/day) and the average of all daily capacity factors value (in percentage) for the 12 models involved in function of the RCM and GCM used.

[6] Each of the reported data is the average of 90 wind power production estimates, one for each simulated year.

Table 4
Daily average wind power production for the 12 ENSEMBLES models (GWh/day).

RCM/GCM	HadCM3	ARPEGE	ECHAM5	BCM	*Average*
RCA3	942				*942*
RM5.1		906			*906*
HIRHAM5		1411	1687	1387	*1495*
CLM	1197				*1197*
RACMO2			1227		*1227*
HadRM3	1315				*1315*
REMO			1198		*1198*
RCA	921		1032	901	*951*
Average	*1094*	*1159*	*1286*	*1144*	***1177***

Table 5
Average wind power capacity factors for the 12 ENSEMBLES models (percentage).

RCM/GCM	HadCM3	ARPEGE	ECHAM5	BCM	*Average*
RCA3	23.2				23.2
RM5.1		22.3			22.3
HIRHAM5		34.8	41.6	34.2	36.8
CLM	29.5				29.5
RACMO2			30.2		30.2
HadRM3	32.4				32.4
REMO			29.5		29.5
RCA	22.7		25.4	22.2	23.4
Average	27.0	28.6	31.7	28.2	**29.0**

Individual ENSEMBLES simulations lead to very different results as far as EU-28 power production is concerned with the highest average daily value (1687 GWh/day for HIRHAM5 driven by ECHAM5) being 87% higher than the lowest average daily value (901 GWh/day for RCA driven by BCM). Ensemble average values (bottom right) leaded to an estimate of 1177 GWh/day produced corresponding to a capacity factor of 29.0%.

It is also interesting to notice that in both tables RCM averages (rows) show a larger diversity than GCM averages (columns) with RCM averages ranging from 22.3% to 36.8% while GCM averages lay between 27% and 31.7% in the case of capacity factors. Moreover, the three highest values of daily production and capacity factors are obtained from simulations using the HIRHAM5 RCM, while three amongst the five lowest capacity factors values are obtained from the RCA RCM. Although the overall amount of simulations is relatively low, these results could suggest *the absolute strength of winds, and then the amount of wind power, being primary driven by the RCM simulation scale*. In Appendix B a deeper analysis of the influence of RCM and GCM models on the results will be provided.

3.3. Wind power correlation

3.3.1. Country-to-country correlation

Table 6 illustrates the correlation between wind power produced in couples of EU countries obtained following the methodology illustrated in Section 2.3.1, showing the time averaged (over 90 years) and ensemble averaged (over 12 models) values of $R^{Y}{}_{i,J}$.

Red shades identify couples of countries strongly correlated, yellow corresponds to couples of country loosely correlated while very little correlated couples of countries ($R_{i,J} < 0.3$) are shown in green shades.

Table 6 helps to identify groups of countries that are particularly correlated each other (in most cases due to their geographical proximity) and to evaluate to what extent these "closed systems" are interrelated with the rest of the continent. An example of closed system is the Iberian Peninsula (top left in Table 6) where Portugal and Spain are strongly correlated each other and uncorrelated with the rest of Europe, with the exception of a slight correlation with France and, in the case of Spain, with Italy. Cyprus (bottom right) is a case of almost fully isolated wind system, with very little correlation ($R_{i,J} \leq 0.2$) with any other countries, including Greece. The Scandinavian and Baltic states (also top left) are also two separate systems, mildly correlated each other, and with somewhat stronger interaction with Northern and Central Europe "bridge" countries such as Denmark, Poland and Germany.

The rest of European countries forms a succession of correlated countries moving from British Isles (mid-top left) to France, BENELUX and Germany and then to the two related but clearly distinguishable blocks of Central European Countries and the Balkans, with Italy showing a intermediate behaviour between these last two groups.

The groups of countries identified on the basis of correlations reflect the main climate patterns in the Euro-Mediterranean region. Indeed, north-western Europe is under the influence of North Atlantic atmospheric circulation patterns [32], while climate variability in north-eastern Europe is modulated by mid and high latitudes circulation patterns over the Eurasian continent [33]. Finally, the Mediterranean region is a transition zone affected by both mid-latitude and tropical circulation systems [34].

Once again, climate effects have been found to be almost negligible. Indeed, very few and very small statistically significant changes in the $R^{Y}{}_{i,J}$ values between different time periods were found. More details are reported in Appendix A.

By comparison, $R^{Y}{}_{i,J}$ values computed by different models have been generally found to be statistically diverse with differences that can be quite relevant in quantitative terms although rarely implying a difference in correlation categorization (high, moderate, low – see Table 6)

In Fig. 8 the example of the average (1961–2050) correlation between Italian and French WE production is shown, illustrating another interesting result of this analysis: different climate models not only lead to different estimates of wind power production because of differently biased wind fields (see Sections 3.1 and 3.2), but *different models found a different time correlation pattern among wind power production in EU countries, probably caused by differences in the way models describe weather regimes on the continental scale.* Such a finding is confirmed by the results presented in next sections.

3.3.2. Country-to-Europe correlation

Fig. 9 and Table 7 show the time (1961–2050) and ensemble (12 models) mean of the $R^{Y}{}_{i,EU}$ coefficients (see Section 2.3.2) in both map and tabular format.

As expected, countries situated in Central Europe show the highest weighted correlation with wind power production from rest of the EU, while the more a country is "peripheral", the less its' wind power production results correlated with the rest of the EU system.

Thus, wind power arising from countries showing a low $R_{i,EU}$ value is more likely to come "at the right moment" in a single European market perspective, i.e., being higher when the rest of Europe is experiencing less wind and lower when in the rest of Europe is experiencing high wind production. As already stated, from a European planning point of view, the availability of such "out of phase" production can help to reduce the need for storage if excess production is exchanged at the right time via properly dimensioned interconnections. From an investor perspective, this means also that the same turbine is likely to sell its production on the common EU market more easily if installed in, say, Portugal or Ireland, rather than Central Europe, for the simple reason that its production time profile is less correlated with the bulk European WE production.

As with the case of country-to-country correlation, country-to-Europe coefficients have shown little if, any, dependence on time

Table 6
Country-to-country correlation for EU-28 countries included in the study. The table shows time (1961–2050) and ensemble (12 models) mean values.

Rij	PT	ES	FI	EE	LV	LT	SE	DK	IE	UK	FR	LU	BE	NL	DE	PL	CZ	AT	SK	HU	HR	SI	IT	RO	BG	GR	CY
PT	1.00	0.80	0.06	0.06	0.07	0.07	0.08	0.06	0.05	0.09	0.34	0.14	0.15	0.10	0.09	0.09	0.10	0.11	0.12	0.10	0.16	0.15	0.23	0.08	0.07	0.05	0.02
ES	0.80	1.00	0.11	0.09	0.10	0.10	0.13	0.08	0.05	0.11	0.50	0.20	0.19	0.12	0.13	0.12	0.15	0.18	0.19	0.17	0.27	0.24	0.40	0.15	0.14	0.14	0.05
FI	0.06	0.11	1.00	0.58	0.44	0.33	0.71	0.21	0.15	0.21	0.17	0.17	0.19	0.19	0.21	0.22	0.17	0.14	0.12	0.08	0.10	0.10	0.12	0.09	0.08	0.07	0.05
EE	0.06	0.09	0.58	1.00	0.87	0.67	0.52	0.28	0.14	0.19	0.16	0.18	0.19	0.20	0.24	0.34	0.19	0.13	0.14	0.09	0.08	0.08	0.09	0.08	0.05	0.04	0.03
LV	0.07	0.10	0.44	0.87	1.00	0.90	0.48	0.33	0.14	0.21	0.18	0.21	0.22	0.23	0.30	0.49	0.26	0.18	0.20	0.14	0.10	0.10	0.10	0.12	0.05	0.02	0.02
LT	0.07	0.10	0.33	0.67	0.90	1.00	0.42	0.36	0.14	0.20	0.18	0.22	0.23	0.24	0.35	0.65	0.34	0.23	0.28	0.19	0.12	0.11	0.12	0.17	0.07	0.01	0.02
SE	0.08	0.13	0.71	0.52	0.48	0.42	1.00	0.49	0.20	0.30	0.21	0.23	0.26	0.28	0.33	0.34	0.23	0.18	0.15	0.10	0.12	0.12	0.14	0.10	0.09	0.08	0.06
DK	0.06	0.08	0.21	0.28	0.33	0.36	0.49	1.00	0.22	0.37	0.21	0.30	0.36	0.48	0.56	0.46	0.31	0.20	0.14	0.10	0.05	0.06	0.07	0.07	0.03	-0.01	0.03
IE	0.05	0.05	0.15	0.14	0.14	0.14	0.20	0.22	1.00	0.75	0.28	0.27	0.36	0.36	0.27	0.17	0.17	0.15	0.10	0.06	0.06	0.07	0.07	0.06	0.06	0.02	0.06
UK	0.09	0.11	0.21	0.19	0.21	0.20	0.30	0.37	0.75	1.00	0.42	0.46	0.60	0.63	0.45	0.25	0.26	0.20	0.13	0.08	0.08	0.10	0.11	0.08	0.07	0.02	0.06
FR	0.34	0.50	0.17	0.16	0.18	0.18	0.21	0.21	0.28	0.42	1.00	0.73	0.72	0.54	0.54	0.28	0.40	0.37	0.27	0.23	0.27	0.32	0.42	0.17	0.12	0.07	0.07
LU	0.14	0.20	0.17	0.18	0.21	0.22	0.23	0.30	0.27	0.46	0.73	1.00	0.89	0.74	0.76	0.36	0.50	0.39	0.27	0.23	0.20	0.26	0.28	0.14	0.08	0.00	0.03
BE	0.15	0.19	0.19	0.19	0.22	0.23	0.26	0.36	0.36	0.60	0.72	0.89	1.00	0.88	0.74	0.34	0.44	0.33	0.21	0.17	0.13	0.18	0.21	0.11	0.07	0.00	0.04
NL	0.10	0.12	0.19	0.20	0.23	0.24	0.28	0.48	0.36	0.63	0.54	0.74	0.88	1.00	0.78	0.37	0.43	0.31	0.19	0.15	0.10	0.14	0.16	0.10	0.06	-0.02	0.04
DE	0.09	0.13	0.21	0.24	0.30	0.35	0.33	0.56	0.27	0.45	0.54	0.76	0.74	0.78	1.00	0.64	0.75	0.58	0.39	0.35	0.22	0.26	0.30	0.24	0.15	0.03	0.05
PL	0.09	0.12	0.22	0.34	0.49	0.65	0.34	0.46	0.17	0.25	0.28	0.36	0.34	0.37	0.64	1.00	0.74	0.55	0.62	0.47	0.26	0.25	0.24	0.38	0.20	0.04	0.05
CZ	0.10	0.15	0.17	0.19	0.26	0.34	0.23	0.31	0.17	0.26	0.40	0.50	0.44	0.43	0.75	0.74	1.00	0.83	0.72	0.59	0.40	0.39	0.42	0.40	0.25	0.10	0.07
AT	0.11	0.18	0.14	0.13	0.18	0.23	0.18	0.20	0.15	0.20	0.37	0.39	0.33	0.31	0.58	0.55	0.83	1.00	0.74	0.68	0.54	0.52	0.60	0.45	0.33	0.18	0.12
SK	0.12	0.19	0.12	0.14	0.20	0.28	0.15	0.14	0.10	0.13	0.27	0.27	0.21	0.19	0.39	0.62	0.72	0.74	1.00	0.87	0.62	0.55	0.49	0.59	0.36	0.15	0.09
HU	0.10	0.17	0.08	0.09	0.14	0.19	0.10	0.10	0.06	0.08	0.23	0.23	0.17	0.15	0.35	0.47	0.59	0.68	0.87	1.00	0.77	0.67	0.55	0.67	0.43	0.19	0.08
HR	0.16	0.27	0.10	0.08	0.10	0.12	0.12	0.05	0.06	0.08	0.27	0.20	0.13	0.10	0.22	0.26	0.40	0.54	0.62	0.77	1.00	0.86	0.73	0.48	0.34	0.20	0.05
SI	0.15	0.24	0.10	0.08	0.10	0.11	0.12	0.06	0.07	0.10	0.32	0.26	0.18	0.14	0.26	0.25	0.39	0.52	0.55	0.67	0.86	1.00	0.59	0.34	0.18	0.07	0.03
IT	0.23	0.40	0.12	0.09	0.10	0.12	0.14	0.07	0.07	0.11	0.42	0.28	0.21	0.16	0.30	0.24	0.42	0.60	0.49	0.55	0.73	0.59	1.00	0.42	0.38	0.36	0.09
RO	0.08	0.15	0.09	0.08	0.12	0.17	0.10	0.07	0.06	0.08	0.17	0.14	0.11	0.10	0.24	0.38	0.40	0.45	0.59	0.67	0.48	0.34	0.42	1.00	0.78	0.37	0.14
BG	0.07	0.14	0.08	0.05	0.05	0.07	0.09	0.03	0.06	0.07	0.12	0.08	0.07	0.06	0.15	0.20	0.25	0.33	0.36	0.43	0.34	0.18	0.38	0.78	1.00	0.67	0.18
GR	0.05	0.14	0.07	0.04	0.02	0.01	0.08	-0.01	0.02	0.02	0.07	0.00	0.00	-0.02	0.03	0.04	0.10	0.18	0.15	0.19	0.20	0.07	0.36	0.37	0.67	1.00	0.21
CY	0.02	0.05	0.05	0.03	0.02	0.02	0.06	0.03	0.06	0.06	0.07	0.03	0.04	0.04	0.05	0.05	0.07	0.12	0.09	0.08	0.05	0.03	0.09	0.14	0.18	0.21	1.00

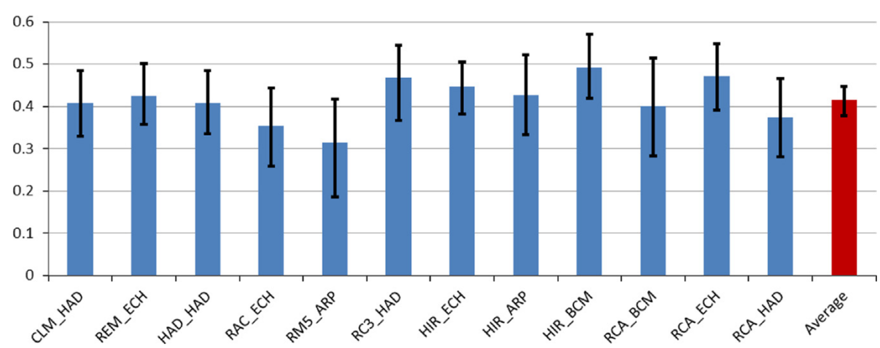

Fig. 8. Average (1961–2050) R correlation between French and Italian wind power production. Bars show the average values computed by each of the 12 models investigated (in blue) and the ensemble mean (in red), while error bars report 10th and 90th percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(see again Appendix A for more details). Instead, individual models provide significantly different values (see Fig. 10 for an example involving both a relatively highly correlated country – Germany – and a quite uncorrelated country – Portugal).

3.3.3. *Synchronicity of European wind power production*

Finally, S^Y values (see Section 2.3.3) were computed as the average of the country-to-Europe $R^Y_{i,EU}$ coefficients weighted with the installed capacity, for each of the model involved in the analysis. Fig. 11 shows the time averaged S^Y value for the 12 models involved (in blue) and the ensemble mean (in red). Error bars report the 10th and the 90th percentiles.

Table 8 shows the average values of S in function of the RCM and GCM used.

It is worth noticing how *S seems at least partially related to the GCM driving the simulation*: For instance, the two largest values of S are found for the only two simulations driven by the BCM model. In other words, S values seem to be more sensitive to the GCM model than the RCM model, the opposite to what was found for the total power production: the issue has been further analysed in Appendix B. Finally, it has to be noted that even in the case of S^Y no evidence of climatic effect was found (see Appendix A for details).

3.3.4. *Sub-continental synchronicity*

The S values reported in Table 8 are difficult to be interpreted in absolute terms, as the present study is the first to apply this indicator to the authors knowledge. Nevertheless, starting from data reported in Table 6 and making use of formulas (7) and (8), it is possible to assess the synchronicity of any subset of the EU countries. As expected, higher values for S were found for groups of countries sharing the same geographical features (e.g., BENELUX countries) than for groups of countries spanning different weather zones (e.g., Germany, Austria and Italy). As a matter of comparison, S value for some groups of countries are reported in Table 9.

Future studies are expected to discuss these findings at the sub-continental scale and their implication for regional electricity markets.

4. Discussion and conclusions

4.1. *Summary of main findings*

The present study has addressed several aspects related to present and future deployment of on-shore wind power in the EU,

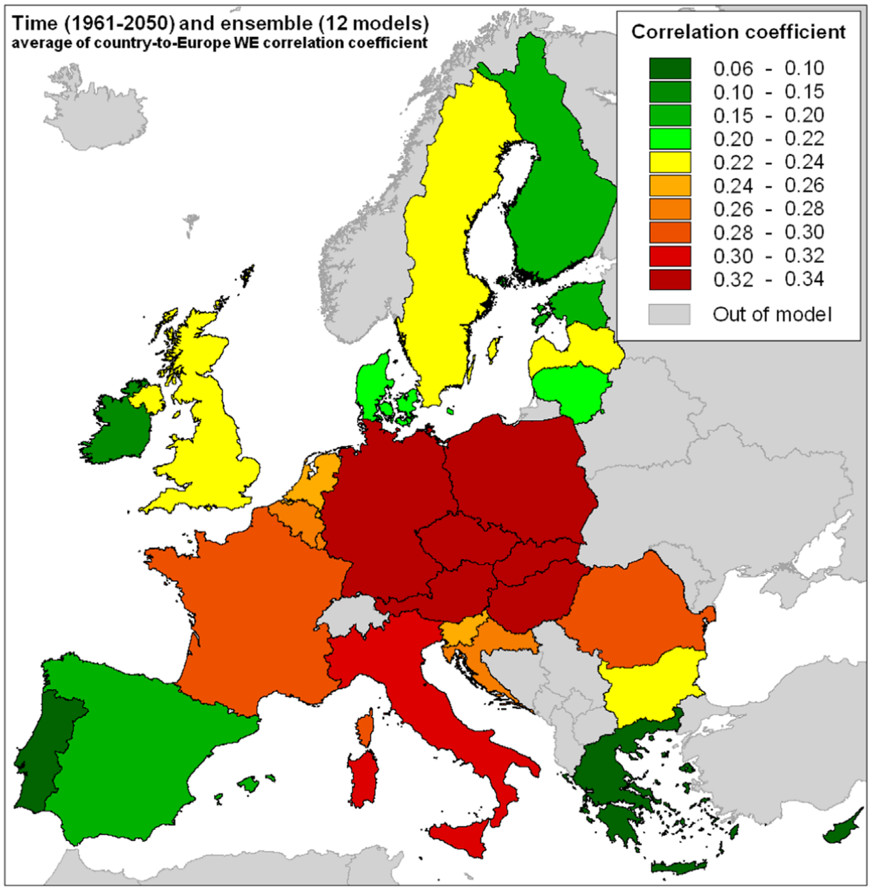

Fig. 9. Country-to-Europe correlation factors for EU countries. The figure shows time (1961–2050) and ensemble (12 models) mean values.

Table 7
Country-to-Europe correlation factors for EU countries. The table shows time (1961–2050) and ensemble (12 models) average values.

Country	$R_{i,EU}$	Country	$R_{i,EU}$	Country	$R_{i,EU}$
DE	0.339	**HR**	0.282	**LT**	0.222
CZ	0.339	**LU**	0.277	**DK**	0.206
HU	0.337	**BE**	0.274	**EE**	0.189
AT	0.332	**NL**	0.265	**FI**	0.178
PL	0.330	**SI**	0.247	**ES**	0.174
SK	0.329	**LV**	0.234	**IE**	0.152
IT	0.312	**BG**	0.233	**GR**	0.099
RO	0.296	**UK**	0.232	**PT**	0.085
FR	0.294	**SE**	0.229	**CY**	0.067

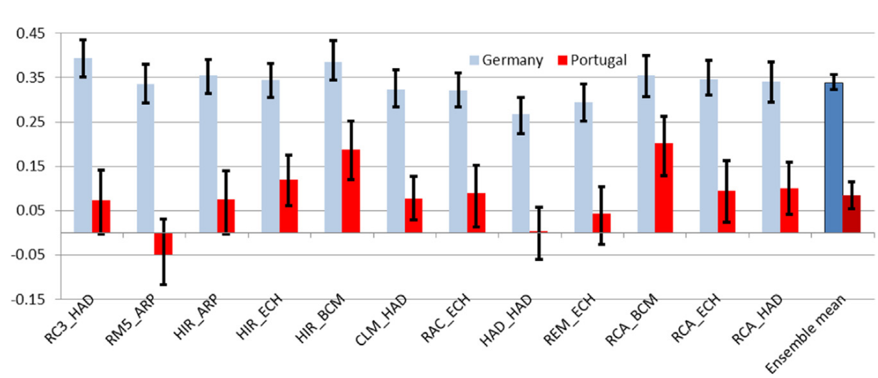

Fig. 10. Average (1961–2050) country-to-Europe correlation coefficients $R^{Y}_{i,EU}$ for Germany (blue) and Portugal (red) WE production. Bars show the average values computed by each of the 12 models investigated (light colours) and the ensemble mean (dark colours), while error bars report 10th and 90th percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

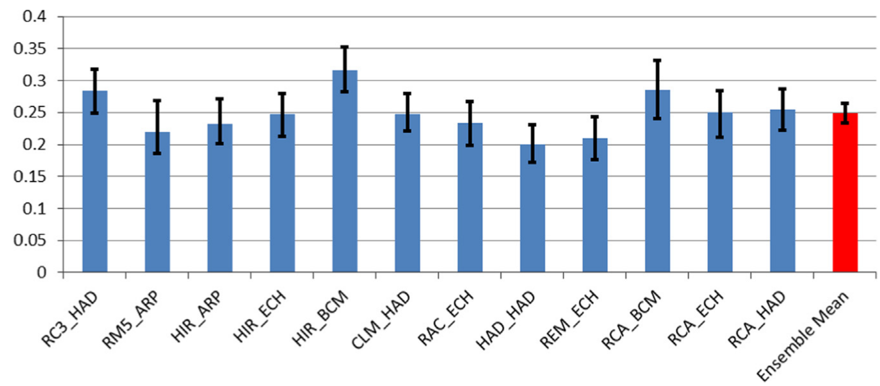

Fig. 11. Average (1961–2050) EU synchronicity indicator S^Y. Bars show the average values computed by each of the 12 models investigated (blue) and the ensemble mean (red), while error bars report 10th and 90th percentiles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 8
Synchronicity factor of EU wind power production for the 12 ENSEMBLES models.

RCM/GCM	**HadCM3**	**ARPEGE**	**ECHAM5**	**BCM**	***Average***
RCA3	0.284				0.284
RM5.1		0.219			0.219
HIRHAM5		0.232	0.247	0.316	0.265
CLM	0.247				0.247
RACMO2			0.234		0.234
HadRM3	0.200				0.200
REMO			0.210		0.210
RCA	0.255		0.250	0.286	0.264
Average	0.247	0.225	0.235	0.301	**0.248**

Table 9
Values of the *S* synchronicity indicator for some groups of EU countries.

Countries	**Synchronicity**	**Countries**	**Synchronicity**
BE-NL-LU	0.876	DE-AT-IT	0.356
EE-LT-LV	0.776	FR-DE-ES	0.323
SE-FI-DK	0.516	ES-IT-GR	0.309

as foreseen in the ENSEMBLES numerical experiment framework and the main findings are summarized.

4.1.1. Climatic effects

Little or no evidence of climate change affecting wind power deployment has been found. From the physical point of view, on-shore Wind Power Density shows few statistically significant trends, if any, in the continent (Fig. 3), very rarely leading a grid point to change Wind Power Class (Fig. 4).

National wind power production also shows little statistical evidence of climate effects (see Appendix A), while significant climate effects are either absent or negligible in the overall EU wind power production.

Finally, country-to-country wind power correlation coefficients show very few cases of significant climate impacts and both in the case of country-to-Europe correlation and the EU synchronicity indicator, no significant climate change effects were found.

4.1.2. Inter-model variability

Both the individual RCM and the GCM models have a profound influence on the overall results. Some statistical evidence was found (see Table B.1) of the RCM having a larger impact on wind power production and the GCM influencing the overall continental synchronicity of the different national power production patterns. The extension of this analysis to further model intercomparison exercises is expected to cast more light on this issue.

4.1.3. Dependence of wind power production on turbine fleet deployment

Thanks to a Monte Carlo based analysis, wind power production has been found to be substantially independent from the actual deployment of capacity fleet. The only constraint applied consisted in assuming countries deploy their wind turbines in areas where wind production is estimated to be above the national average.

4.1.4. Wind power production and capacity factors

Considering the 2020 installed capacity planned in NREAPS (totalizing 169 GW), the average EU capacity factor has been found to be 29%, and the average daily production amounting to 1177 GWh/day. A large variation in these results depending on the models employed was also found (see Tables 4 and 5), while all the models have confirmed the seasonal pattern of wind production (see Fig. 7) although again quantitatively differently between models.

4.1.5. Wind power correlation patterns

Wind power production correlates differently for different country couples and "clusters" of similarly behaving countries could be identified (Table 6) consistent with the main meteorological features of the European weather system. Country-to-Europe correlation coefficients have shown how peripheral countries generally provide wind power production less correlated with the rest of the EU production (Fig. 9). Implications of this result for the EU transmission grid will be discussed in the next section.

4.1.6. Wind power synchronicity in the EU

An indicator for the overall synchronicity of the EU wind power production has been developed and its model related variability was discussed. Future work is expected to apply the indicator to sub-sets of EU countries in order to assess the complementarity features of regional wind electricity markets.

4.2. Implications for EU wind power transmission

Table 6 and Fig. 9 summarize the results of the present study having the most relevant implications for the EU power transmission system. Generally speaking, the less wind power production from two countries is correlated, the more the two power productions are expected to complement each other and the more power exchange will be beneficial to both countries. In terms of Fig. 9, the less wind power production in a country is correlated with power production in the rest of the EU, the more exchanging its power will be beneficial on average to other countries.

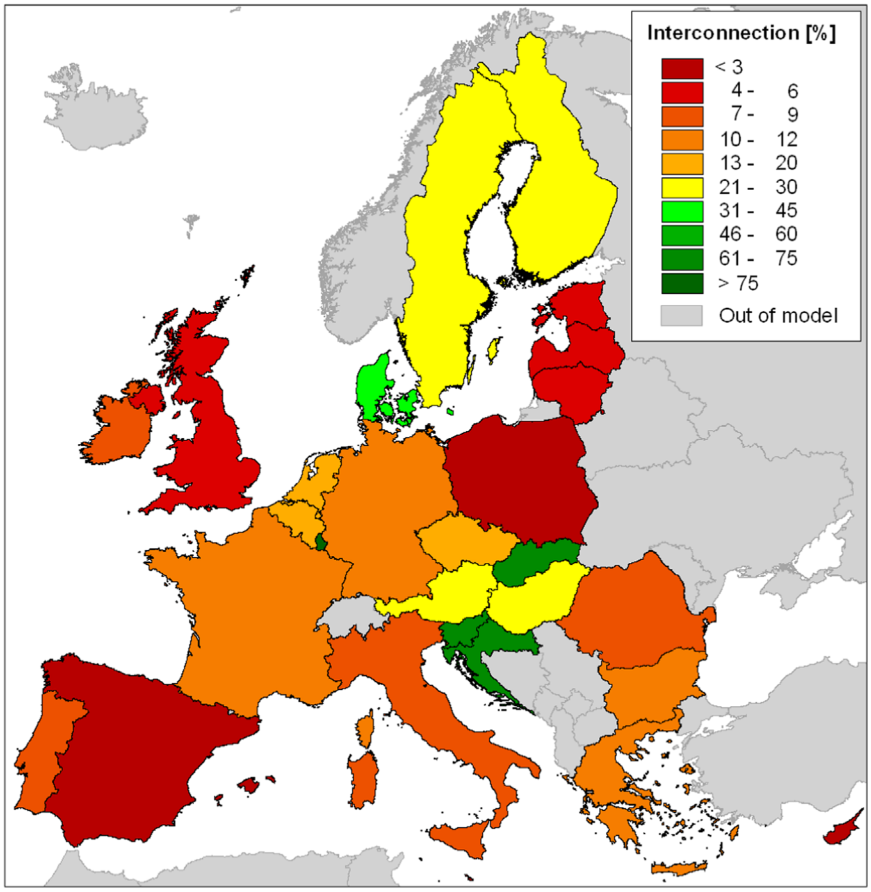

Fig. 12. Interconnection levels for electricity for EU countries in 2014. Data show the ratio between interconnection capacity and total power production capacity (in percentage).
Source: EC – European Commission [35].

In other words, countries showing low correlation values in Fig. 9 should be the more interconnected ones in order to allow their "out of phase" wind power production to easily reach the whole EU market.

On the contrary, Fig. 12 shows how this is not always the case in the present EU transmission grid, and there are several cases of countries potentially providing wind power well complementary to the EU production being little or very little interconnected with neighbour countries, as it is the case of Spain, the UK and, to a smaller extent, of Ireland and Greece.

Plans are already in place to increase interconnection levels to 10% minimum in the EU [30] and the present study is further strengthening the benefits arising from such an approach, showing as wind electricity flowing freely among countries showing different production patterns could benefit the whole system stability through complementarity.

4.3. Open issues and outlook for future research

Some points remain open after the present study, providing guidelines for further future analyses.

1. Results arising from other combinations of GCM/RCM should be included in order to further populate Tables 4, 5 and 8 and better addressing the issue of model scales.
2. A similar analysis could be produced based on retrospective data from e.g., reanalysis in order to assess synchronicity, correlation and power production values closer to the actual past wind features.
3. More details could be provided on specific subsets of countries in order to guide regional markets.
4. As the ENSEMBLES data set provided daily values only, intraday correlation analysis has not been possible. Such an analysis could provide further insights on short term power exchanges among EU countries, allowing taking into consideration time shifts between daily cycles spread in a geographical area spanning about 40° of longitude and 35° of latitude.
5. The methodology developed here can be easily extended in order to include other sources such as off-shore wind and solar energy, provided reliable data are available.

Disclaimer

The views expressed in this paper are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

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Appendix A. Climate impacts on wind power production and complementarity: Detailed statistics results

Following the methodology applied in [8], the statistical evidence of changes in key variable related attributable to *climate effects* was assessed comparing the "present" time period (1991–2010) with the mid-century period (2031–2050) by means of *t*-test looking for 95% ($p<0.05$) significance. Consistently with the discussion in Section 3.1.2, the average values of the $N=10$ different wind power fleet allocations were considered.

A.1. Wind power production

Table A.1 shows the results of such tests for the *annual wind power production* 27 countries studied and for the 12 ENSEMBLES models and their ensemble mean. Significant differences were found in just 27 cases out of 324 possible country/model combinations and were never found by more than three models for each country (see N_m column in Table A.1). On the contrary, 17 out of the 27 significant wind power variations were found by just three models, namely RC3_HAD, CLM_HAD and HAD_HAD all sharing the same GCM, while half of the model tested found no or just one case of significant differences. Wind power production changes, even when statistically significant, were in any case quite small, rarely overcoming 5% and lower than 2% in the case of ensembles averages.

Finally, the last line in Table A.1 shows how only three models found a significant change in the total wind power production, never higher than 3%, with ensemble mean not showing any significant change.

A.2. Wind power correlation

Table A.2 shows the results of the *t*-tests for country-to-Europe complementarity coefficients (see Section 2.3.2) for the 27 countries studied and for the 12 ENSEMBLES models and their ensemble mean. Significant differences were found in just 25 cases out of 324 possible country/model combinations and were never found by more than three models for each country (see N_m column in Table A.2). On the contrary, 14 out of the 25 significant coefficients variations were found by just two models, namely HIR_ECH and RCA_BCM, different from the ones that have shown the largest number of significant wind power variations. Two thirds of the models tested found no or just one case of significant differences and significant coefficient changes ranged between +0.057 to −0.054. Finally, the last line in Table A.1 shows how only one model found a significant change in the EU synchronicity factor amounting to an increase of 0.022.

Appendix B. Impacts of RCM and GCM on wind power and its time patterns in ENSEMBLES runs

Data contained in Tables 6 and 8 have been analysed through single factor ANOVA in order to determine a statistical evidence for the influence of RCM and/or GCM to the results obtained. *p*-Values obtained are reported in Table B.1

Table A.1
Percentage differences in average wind power production between "future" (2031–2050) and "present" (1991–2010) scenarios for each country and ENSEMBLES model investigated. Statistically significant differences at 95% level are highlighted in red. N_c reports the number of countries for which each model has found a statistically significant difference, while N_m in the number of models that found a statistically significant difference for each country.

	RAC_ECH	RC3_HAD	RM5_ARP	HIR_ARP	HIR_BCM	HIR_ECH	CLM_HAD	HAD_HAD	REM_ECH	RCA_BCM	RCA_ECH	RCA_HAD	N_m	ENS. MEAN
Belgium	0.4%	-5.0%	-0.7%	-0.9%	2.3%	-1.4%	-0.2%	0.5%	-0.3%	2.3%	-1.0%	-2.0%	1	-0.5%
Bulgaria	0.9%	-3.4%	4.8%	1.6%	2.6%	-2.2%	-2.8%	-2.1%	0.2%	1.2%	-1.0%	-0.4%	0	-0.2%
Czech Rep.	-1.3%	-1.4%	-2.0%	-1.0%	2.3%	-1.8%	-1.3%	-0.5%	-1.2%	0.5%	-2.5%	0.1%	0	-0.8%
Germany	-0.9%	-3.1%	-0.9%	-1.0%	2.3%	-1.0%	-0.1%	1.9%	-1.1%	3.3%	-2.7%	0.0%	1	-0.3%
Denmark	-1.2%	-1.5%	-0.5%	-1.6%	1.8%	0.2%	1.5%	1.8%	-1.1%	2.4%	-2.4%	-0.4%	0	-0.1%
Estonia	1.4%	-0.8%	0.1%	-0.3%	1.3%	1.1%	2.8%	0.3%	0.4%	-0.5%	-3.0%	0.5%	0	0.4%
Ireland	-0.5%	-4.3%	-0.6%	-1.9%	1.7%	0.0%	1.5%	3.8%	-2.0%	5.4%	-1.5%	-0.8%	3	-0.1%
Greece	0.7%	-0.5%	2.4%	1.8%	1.9%	-0.4%	-1.4%	-3.7%	0.1%	3.5%	1.3%	3.5%	1	0.5%
Spain	-1.5%	1.9%	3.0%	3.1%	-0.6%	-2.2%	-1.6%	0.5%	-2.8%	1.2%	-1.9%	-0.4%	0	-0.3%
France	-0.3%	0.1%	1.2%	0.0%	0.0%	-3.6%	-3.5%	0.1%	-3.2%	1.2%	-3.2%	-0.4%	3	-0.8%
Croatia	0.2%	-1.9%	-1.3%	-2.2%	-0.8%	-0.6%	-6.5%	-5.6%	0.0%	-4.6%	0.7%	0.2%	2	-2.0%
Italy	1.2%	0.0%	0.3%	-0.8%	1.7%	0.4%	2.1%	0.1%	0.0%	-0.4%	-2.9%	-0.3%	0	0.1%
Cyprus	-0.3%	-0.9%	-1.0%	-0.3%	2.0%	0.8%	3.0%	1.6%	-1.0%	0.6%	-3.6%	-0.5%	0	0.2%
Latvia	0.4%	1.0%	-0.2%	-1.3%	1.5%	-0.1%	1.6%	0.7%	-0.8%	0.8%	-2.9%	-0.5%	0	0.0%
Lithuania	-0.7%	-5.0%	-3.5%	-1.2%	3.0%	-1.2%	-1.0%	0.1%	-1.0%	3.1%	-1.7%	-1.4%	1	-0.8%
Luxembourg	0.0%	-4.3%	-0.4%	-0.1%	1.1%	-0.8%	-1.0%	0.1%	-0.3%	2.4%	-1.9%	0.5%	1	-0.4%
Hungary	-1.2%	-3.7%	1.4%	1.2%	1.1%	-1.8%	-3.5%	-2.5%	-2.4%	1.9%	-2.0%	0.7%	1	-1.0%
Netherlands	-1.2%	-2.8%	-5.1%	-2.0%	2.6%	-2.0%	-3.4%	-1.6%	-2.5%	1.5%	-2.8%	-0.4%	1	-1.8%
Austria	-1.3%	-0.5%	-1.5%	-1.4%	1.6%	-1.6%	-0.2%	1.6%	-1.0%	0.1%	-3.0%	-0.9%	0	-0.7%
Poland	-1.8%	1.1%	-2.2%	-2.2%	2.2%	-0.5%	-5.7%	-1.1%	-0.4%	-0.4%	-1.9%	1.4%	1	-0.8%
Portugal	-1.0%	-1.1%	2.9%	0.8%	0.5%	-2.0%	-2.8%	-1.2%	-0.7%	-2.1%	-2.5%	-0.5%	0	-0.9%
Romania	-2.9%	0.2%	-0.8%	-0.2%	0.5%	-3.0%	-2.4%	-0.5%	-3.1%	-0.5%	-3.9%	-0.6%	2	-1.5%
Slovenia	-1.3%	-3.4%	-0.5%	-0.1%	0.1%	-0.6%	-5.5%	-4.0%	-2.0%	-2.1%	-2.7%	-0.4%	2	-1.8%
Slovakia	-1.3%	1.0%	0.5%	3.3%	-1.4%	-3.7%	-3.6%	1.4%	-2.8%	1.4%	-2.3%	-1.9%	1	-1.0%
Finland	-0.4%	-4.3%	-0.1%	-0.2%	2.9%	-0.7%	-1.4%	-0.3%	-1.7%	3.4%	-1.4%	-2.2%	3	-0.5%
Sweden	-0.3%	0.2%	-0.9%	0.5%	2.4%	-0.5%	2.8%	1.8%	-1.5%	3.6%	-2.2%	-0.8%	2	0.4%
United King.	-0.2%	-4.0%	-0.8%	-1.3%	0.5%	-0.9%	1.0%	1.2%	-2.1%	1.5%	-1.1%	-2.3%	1	-0.7%
N_c	0	7	1	0	2	2	6	4	1	3	1	0	27	4
EU Total	-0.7%	-3.0%	-0.5%	-0.5%	1.4%	-0.9%	-1.6%	-0.3%	-1.5%	1.5%	-2.1%	-0.6%		-0.7%

Table A.2
Differences in average country-to-Europe complementarity coefficients (see Section 2.3.2) between "future" (2031–2050) and "present" (1991–2010) scenarios for each country and ENSEMBLES model investigated. Statistically significant differences at 95% level are highlighted in red. N_c reports the number of countries for which each model has found a statistically significant difference, while N_m in the number of models that found a statistically significant difference for each country. The last line reports results for the synchronicity coefficient for Europe as defined in Section 2.3.3.

	RAC_ECH	RC3_HAD	RM5_ARP	HIR_ARP	HIR_BCM	HIR_ECH	CLM_HAD	HAD_HAD	REM_ECH	RCA_BCM	RCA_ECH	RCA_HAD	N_m
Belgium	0.000	-0.003	-0.012	0.001	0.018	0.023	0.008	-0.007	0.010	0.024	0.012	0.008	2
Bulgaria	-0.009	-0.032	-0.031	-0.010	0.004	-0.012	-0.018	-0.017	-0.006	-0.014	0.001	-0.017	0
Czech Rep	0.004	0.004	-0.011	-0.004	0.007	0.018	0.010	-0.004	0.006	0.028	0.012	0.008	1
Germany	-0.004	0.000	-0.023	-0.006	0.019	0.027	-0.004	-0.006	0.003	0.021	0.003	0.012	0
Denmark	-0.001	0.011	-0.016	0.000	0.025	0.009	-0.008	-0.001	-0.002	0.024	0.006	0.021	0
Estonia	0.007	0.014	-0.031	-0.002	0.007	0.005	-0.001	-0.027	-0.003	0.037	0.006	-0.018	1
Ireland	0.010	0.013	-0.012	0.008	0.017	0.023	-0.001	-0.013	0.014	0.043	0.012	-0.002	1
Greece	-0.005	-0.005	-0.054	-0.037	-0.017	-0.024	-0.057	-0.014	-0.001	-0.021	-0.008	-0.021	3
Spain	-0.011	0.006	-0.017	-0.001	0.002	0.036	-0.026	-0.027	0.000	0.002	-0.003	0.017	1
France	0.005	0.000	-0.011	0.005	0.015	0.020	0.003	-0.008	0.013	0.024	0.013	0.005	0
Croatia	0.002	-0.022	-0.018	-0.018	0.006	0.009	0.002	-0.009	0.001	0.028	0.008	-0.004	0
Italy	0.002	-0.009	-0.014	-0.018	0.006	0.016	-0.003	-0.021	0.006	0.026	0.001	0.013	0
Cyprus	-0.005	0.010	-0.041	-0.008	0.009	0.027	-0.006	-0.034	-0.001	0.057	0.001	0.010	3
Latvia	0.014	0.010	-0.019	0.002	0.020	0.012	0.002	-0.033	0.003	0.040	0.013	-0.005	2
Lithuania	0.012	0.006	-0.018	0.007	0.018	0.013	0.004	-0.029	0.010	0.040	0.018	0.009	2
Luxembou	-0.001	-0.005	-0.007	-0.001	0.014	0.018	0.006	-0.007	0.009	0.025	0.007	0.007	1
Hungary	0.002	-0.002	-0.029	-0.008	0.025	0.010	0.004	-0.009	0.000	0.022	0.014	0.004	0
Netherlan	-0.003	0.000	-0.018	0.001	0.014	0.024	0.008	-0.006	0.007	0.024	0.011	0.010	2
Austria	0.001	-0.003	-0.007	-0.002	0.010	0.020	0.007	-0.014	0.009	0.021	0.017	0.005	0
Poland	0.010	0.007	-0.016	-0.011	0.018	0.016	0.010	-0.010	0.016	0.039	0.016	0.017	1
Portugal	-0.031	0.005	0.003	0.017	-0.008	0.029	-0.009	-0.006	-0.016	-0.030	-0.025	0.002	0
Romania	0.006	-0.012	-0.028	-0.010	0.019	-0.003	-0.002	-0.018	0.017	0.002	0.016	-0.016	0
Slovenia	-0.005	-0.022	-0.007	-0.015	0.019	0.003	0.010	0.002	-0.008	0.025	0.003	-0.003	1
Slovakia	0.019	0.006	-0.028	-0.012	0.018	0.022	0.009	-0.012	0.014	0.026	0.026	0.010	2
Finland	0.004	0.024	-0.028	0.002	-0.008	0.005	-0.003	-0.012	-0.004	0.011	-0.004	-0.033	1
Sweden	0.008	0.013	-0.030	-0.007	0.009	0.009	-0.012	-0.012	0.005	0.024	0.009	-0.005	1
United Kir	0.009	0.009	-0.013	-0.001	0.005	0.021	-0.003	-0.012	0.012	0.014	0.016	-0.001	0
N_c	0	1	3	1	0	4	1	3	0	10	1	1	25
S_EU	-0.002	0.002	-0.018	-0.004	0.009	0.022	-0.009	-0.014	0.005	0.014	0.004	0.007	

Table B.1
p-Values for ANOVA analysis on the dependence of power production and synchronicity factor from GCM and RCM.

Model/Indicator	**Power**	**Synchronicity**
RCM	0.06	0.57
GCM	0.79	0.06

Because the lower the *p*-value found, the higher is the influence of the RCM/GCM used on the variability of the indicator assessed, Table B.1 results confirm that *wind power production is more strongly influenced by the RCM than the GCM*, as already qualitatively discussed in Section 3.2. On the contrary, *EU wind power synchronicity seems to be more deeply influenced by the GCM than the RCM.*

These results confirm to some extent the physical intuition that wind power absolute values are more related to the way RCM models deal with local aspects having a direct impact on wind strength, such as orography or sea breezes. On the contrary, the observations of statistically different *S* values coming from different models leads to the hypothesis that *ENSEMBLES GCM models differently describe the time evolution of wind patterns on the European continent, with some models describing a EU wind system more "concordant", with winds growing and decreasing more synchronously than in other models.*

Nevertheless, it is worth noticing that values in Table B.1 provide an indication, but still not a definitive proof of the effects described. Indeed, a *p*-value of 0.06 is not always considered robust enough to take conclusions. The extension of the analysis performed in this study to other numerical experiments leading to filling the gaps in Tables 6 and 8 could cast more light on this issue.

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