Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 153 (2018) 22–28

Energy Procedia

www.elsevier.com/locate/procedia

5th International Conference on Energy and Environment Research, ICEER 2018

Impact of strong climate change on the statistics of wind power generation in Europe

Juliane Weber[a,b,*], Fabian Gotzens[a], Dirk Witthaut[a,b]

[a]Forschungszentrum Jülich, Institute of Energy and Climate Research - Systems Analysis and Technology Evaluation (IEK-STE), 52425 Jülich, Germany

[b]University of Cologne, Institute for Theoretical Physics, Zülpicher Str. 77, 50937 Cologne, Germany

Abstract

Variable renewable energy sources highly rely on weather and climate variability. Therefore, their power output may become subject to climate change. We analyze how strong climate change may affect wind power resources in Europe, based on the outcome of high-resolution climate simulations. In particular, we evaluate the probability and persistence of low, medium and high wind regimes and the seasonal variability of wind speeds. For many parts in Europe we find a shift in the wind speed distribution: from higher to smaller wind velocities. Thus, the occurrence of wind velocities smaller than the cut-in velocity becomes more likely, which may result in lower wind power output. We further observe an increasing seasonal wind variability over most of Central and North-Western Europe. This may enhance curtailment in the winter months and backup energy needs in summer.

Keywords: climate change; wind power statistics; seasonal wind variability; EURO-CORDEX

1. Introduction

The mitigation of climate change requires the rapid decarbonization of the energy system. Fossil-fueled power

* Corresponding author. Tel.: +49-2461-61-1722; fax: +49-2461-61-2540
E-mail address: j.weber@fz-juelich.de

1876-6102 © 2018 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)
Selection and peer-review under responsibility of the scientific committee of the 5th International Conference on Energy and Environment Research, ICEER 2018.
10.1016/j.egypro.2018.10.004

plants must be replaced by renewable energy sources such as wind and solar power to achieve the 2°C goal of the Paris agreement [1, 2]. These renewable sources have shown a remarkable development in the last decades [3, 4], but system integration remains a challenge due to their intrinsic volatility [4-13]. The rise of renewables constitutes a new direct link between climate and energy systems [5, 12]. Wind and solar power generation are determined by current wind speeds and solar irradiation and are thus highly volatile. The realization of a renewable power system therefore requires a deeper understanding of the impact of climatic conditions and their potential change in the future.

A variety of previous studies has addressed the total annual wind power yield [14-19] showing a limited effect of climate change. [9, 16, 17] further show that the seasonal wind variability tends to increase in many Central and North-Western European countries. In this contribution, we discuss the impact of climate change on statistical features of wind resources beyond total power yields. In particular, we analyze the statistics and persistence of low, medium and high wind regimes. They correspond to the three regimes observed in a typical power curve of a wind turbine: no generation, generation proportional to the third power of the wind velocity and constant power output. Furthermore, we discuss changes in the seasonal wind variability by means of Fourier coefficients. Our results should be understood as an assessment to reveal potential changes in wind statistics if mankind fails to prevent strong global warming.

2. Methodology

We analyze wind speed time series for a strong climate change scenario – the representative concentration pathway 8.5 (RCP8.5) [20]. This scenario is chosen as it provides an upper boundary of the possible impact of climate change. The analysis is based on five state-of-the-art global climate models (GCMs) downscaled to a high spatial and temporal resolution (0.11° and 3 h) by the EURO-CORDEX initiative [21, 22] using the regional climate model RCA4 [23, 24]. We compare results for the end of the century ('eoc', 2070-2100) to results of a historical time frame ('h', 1970-2000) for the five climate models. A result is denoted as robust if at least four of the five models agree on the sign of change. Due to the limited availability of highly resolved climate projections, our analysis is restricted to Europe.

Unfortunately, wind speeds are only given at a height of $z_0 = 10$ m, which is far below the height of a typical wind turbine. It is common practice to use a simple power law in order to extrapolate the wind velocities v to the hub height z of a wind turbine [18, 19, 25]:

$$v_z = v_{z_0} \left(\frac{z}{z_0}\right)^{\alpha} \tag{1}$$

We chose $z = 100$ m and $\alpha = 1/7$. Other choices of z and α were also tested, but since we are only interested in absolute and relative changes, our results do hardly depend on the exact choice of these parameters.

A wind turbine operates differently for different wind regimes. For wind velocities v smaller than the cut-in velocity $v_{\mathrm{cut-in}}$, the power generation is zero. Between $v_{\mathrm{cut-in}}$ and the rated wind speed v_{rated}, the wind power output is proportional to v^3 [25] and for $v \geq v_{\mathrm{rated}}$, the power output is constant. Furthermore, for very high wind speeds $v \geq v_{\mathrm{cut-out}}$, wind turbines have to be shut down for safety reasons. We chose $v_{\mathrm{cut-in}} = 3\ \mathrm{m/s}$, $v_{\mathrm{rated}} = 12\ \mathrm{m/s}$ and $v_{\mathrm{cut-out}} = 25\ \mathrm{m/s}$. Since wind velocities above $25\ \mathrm{m/s}$ are hardly observed over continental Europe and we only find very weak changes at common offshore regions, we just consider the regimes

- r1: $v < v_{\mathrm{cut-in}}$,
- r2: $v_{\mathrm{cut-in}} \leq v < v_{\mathrm{rated}}$,
- r3: $v \geq v_{\mathrm{rated}}$

in our analysis.

We analyze the probability and the persistence time of wind velocities being in one of the three regimes. The persistence times can be represented by a duration curve, i.e. the probability for an event to last for at least x hours. However, we cannot present a duration curve for each site in Europe. Therefore, we consider the duration x associated with the 95 % quantile of the duration distribution. This means, 95 % of the data have a duration smaller than x hours and 5 % of the data have a duration longer than x hours. In order to represent the impact of climate change on long persistence times, we derive the absolute change of the duration which corresponds to the 95 % quantile of the duration distribution.

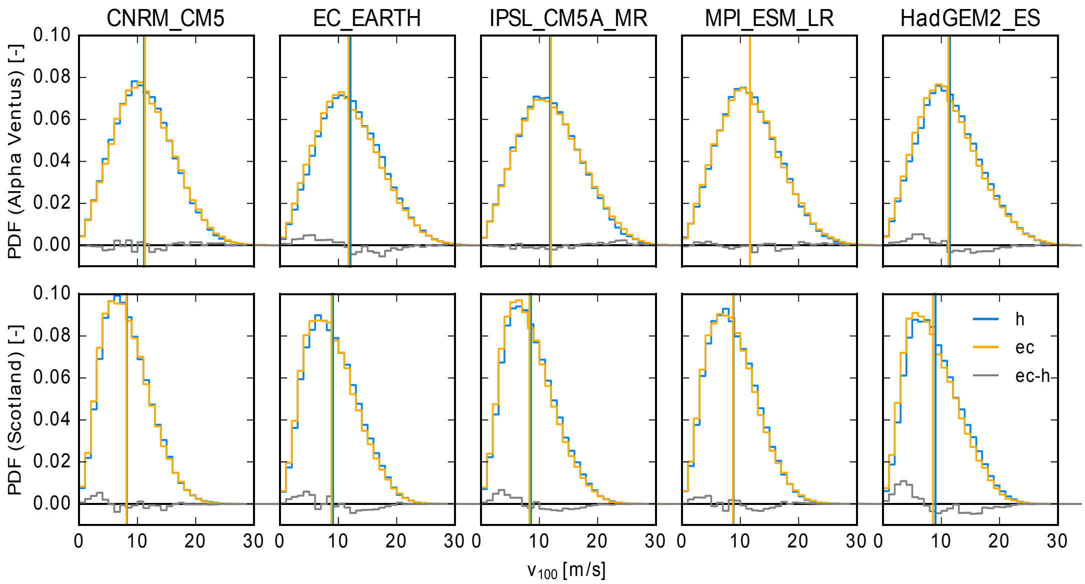

Fig. 1. Probability density function (PDF) of wind speeds v_{100} at a height of 100 m at the offshore site Alpha Ventus (lat/lon = 54.0°/6.4°) and at one point in Scotland (lat/lon = 57.0°/−2.9°) for the five models. Vertical lines show the average wind velocity. Blue: historical (1970-2000), yellow: end of century (2070-2100), grey: difference.

A further important statistical feature of a wind time series is its seasonal variability. Usually, wind speeds are higher in winter than in summer over Europe. In order to quantify the impact of climate change on this seasonality, we analyze the relative change of the peak of the Fourier spectrum that corresponds to a frequency of 1/year.

3. Results

3.1. Exemplary results for two sites in Europe

The probability density function (PDF) of the 100-m wind speeds is shown for two examples in Fig: the offshore site 'Alpha Ventus' in the North Sea and one point in Scotland. For Alpha Ventus, predicted changes in the PDF differ between the five models. In the case of Scotland, the distributions show a weak shift from high to low wind velocities. The average wind velocities are hardly sensitive to climate change and relative changes are of the order of ± 0 to 5 %. Even though changes in average wind speeds may be low, there might be a strong impact on wind power output due to the highly nonlinear relationship between wind velocities and wind generation. Furthermore, results strongly depend on the explicit location. Thus, there is a need for a more detailed statistical analysis for Europe as a whole.

3.2. Probability of being in one of the three wind regimes

A shift from high to low wind velocities can have significant implications for wind power generation due to the three regimes in the power curve. Therefore, we will analyze the change of the probability of being in one of the three regimes for Europe as a whole in the following (see Fig). We find a robust (i.e. at least four of the five models agree on the sign of change) shift from regime r2 ($3 \leq v < 12$ m/s) to regime r1 ($v < 3$ m/s) over most of continental Europe, whereas there is almost no shift between r3 ($v \geq 12$ m/s) and r2. Exceptions are Spain, Norway and the Alps, where we find a shift from r3 to r2 and r1. We further find a shift from regime r3 to regimes r2 and r1 over the Atlantic

Ocean and the Mediterranean Sea. It should be noted that the probability for small wind speeds ($v < 3$ m/s) is much lower over the ocean than over land (cf. Fig). Therefore, a small absolute change of $P(v < 3)$ over the ocean implies a comparatively high relative change. The same is true for $P(v \geq 12)$ over land. However, the models do not agree on the sign of change over most of continental Europe for $P(v \geq 12)$.

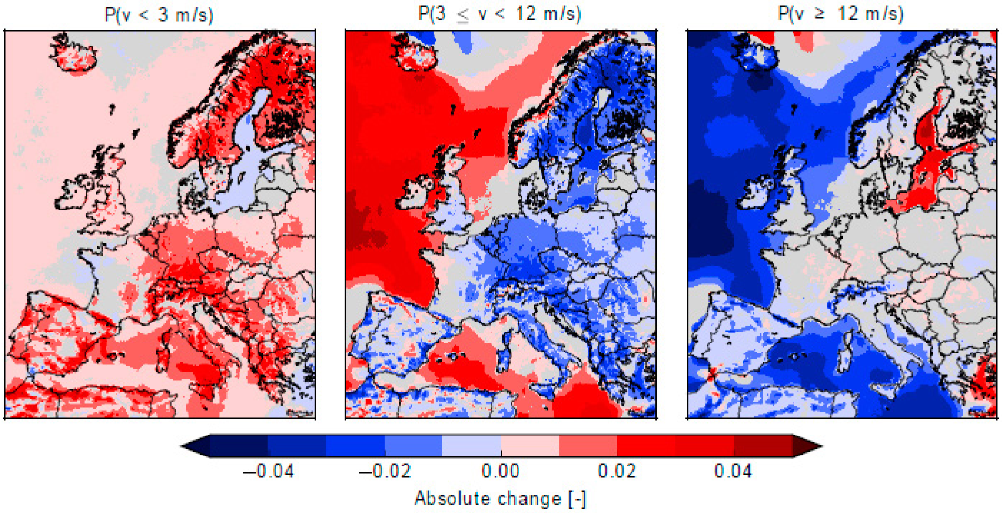

Fig. 2. Average absolute change of the probability for wind speeds being in one of the three wind regimes. The average is derived from the absolute change found for each of the five models. Sites are colored in grey if less than four of the five models agree on the sign of change.

All in all, over many parts of Europe we find a negative effect of strong climate change for the generation of wind power: The probability for being below the cut-in velocity increases and there is a general shift from higher to lower wind velocities in many parts of Europe. A complementary effect arises over the Baltic Sea, the Aegean Sea and the Strait of Gibraltar: There is a shift to higher wind velocities from r1 and r2 to r3. Yet, offshore wind generation in these regions may become more effective under strong climate change.

3.3. Persistence times

The wind time series have a temporal resolution of 3 h. Therefore, the duration of being in one of the three wind regimes is a discrete value (a multiple of three). We decided to analyze the absolute change in the duration corresponding to the 95 % quantile of the duration distribution. A signal is denoted as robust if at least four of the five models agree on either an increase in the duration, no change at all or a decrease.

Even though we find a robust increase of being in wind regime r1 for most of Europe (cf. Fig), this does not automatically imply that the persistence time of being in this regime increases as well (see Fig). In fact, for regime r1 we only find a robust increase in the persistence time for Sweden, Finland and Estonia and partly also for Latvia and spots in Central Europe. For many sites, especially in Southern Europe and at the coastal regions, we find no change at all and for most sites, the models do not agree on the sign of change.

This observation is different for regime r2. Here, increasing probabilities over the Atlantic Ocean and parts of the Mediterranean Sea also imply a longer persistence of being in this state. We further find longer persistence times in the North Sea, even though there is no robust change of the probability there. Additionally, over large parts of Central, Eastern and Southern Europe, the persistence time corresponding to the 95 % quantile decreases. This may result from the decreasing probability of being in this regime and from a higher probability to switch between regimes r1 and r2.

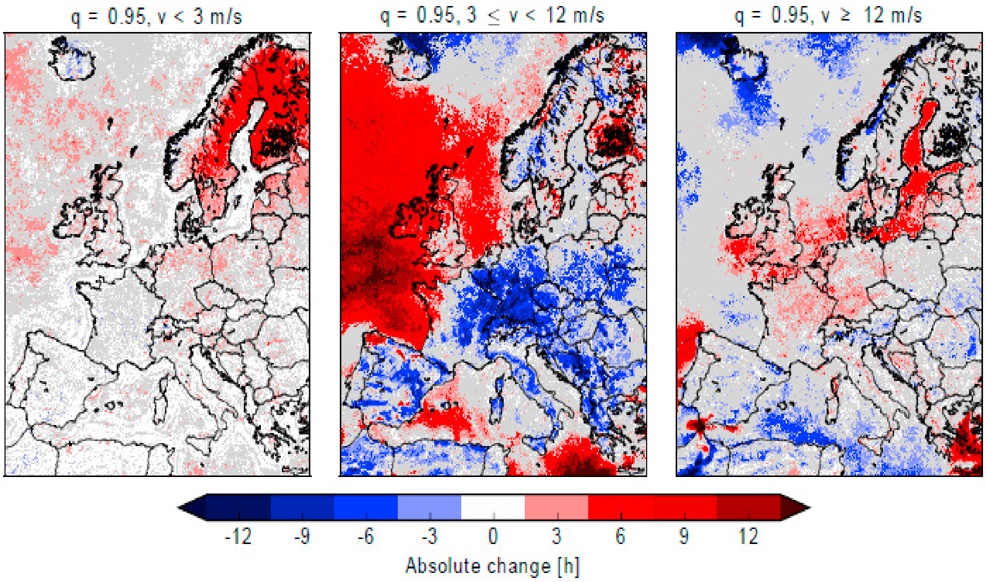

Fig. 3. Average absolute change of the persistence corresponding to the 95 % quantile of the duration distribution for the three wind regimes. The average is derived from the absolute change found for each of the five models. Sites are colored in grey if less than four of the five models agree on the sign of change.

For high wind velocities ($v \geq 12$ m/s, r3), the persistence times increase over the Baltic Sea, the North Sea, the Aegean Sea, the Strait of Gibraltar and partly over the UK, Ireland, Germany, Benelux, France and the Baltic states. As this wind regime implies a constant power generation at rated capacity, we can conclude that strong climate change may have a positive impact on the steadiness of wind generation in these regions.

To conclude, for the low and the high wind regime, we observe at all sites in the northern part of Europe (except for Norway) which are relevant for wind power generation either an increasing persistence time or no change at all.

3.4. Seasonal wind variability

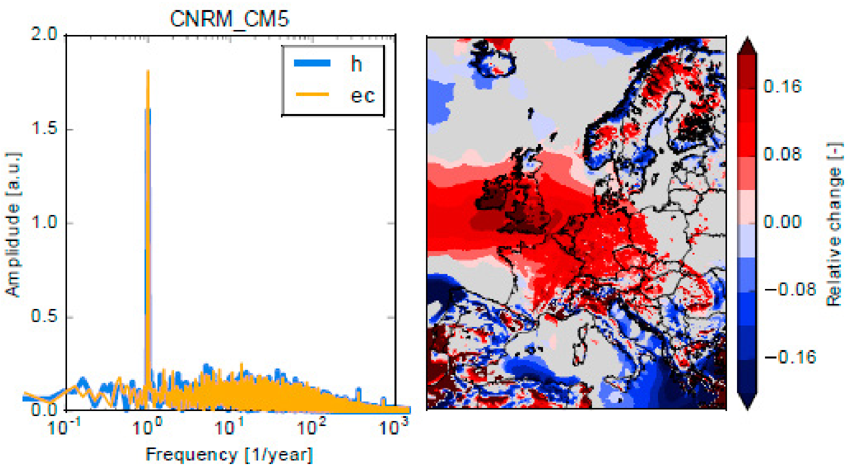

Fig. 4. Left: Frequency spectrum for one model in the EURO-CORDEX ensemble. Right: Average relative change of the height of the peak in the Fourier spectrum corresponding to a frequency of 1/year. The average is derived from the relative change found for each of the five models. Sites are colored in grey if less than four of the five models agree on the sign of change. Blue: historical (1970-2000), yellow: end of century (2070-2100).

The wind yield in Europe is usually higher in winter than in summer. An increasing seasonal wind variability would refer to higher wind yields in the winter months and/or lower wind yields in the summer months. This is not favorable for renewable power systems that highly rely on wind energy as there is lots of overproduction in winter and/or lots of backup needed in summer.

We find an increasing Fourier component corresponding to the seasonal variation of wind speeds for Germany, UK, Ireland, Benelux, the Czech Republic and France (see Fig). For Southern Europe results are often not robust. However, in some Regions in the Mediterranean Sea, Spain, Portugal and Greece, we observe a strong decrease in the seasonal wind variation, which is favorable for a wind-dominated power system. Changes are not robust in the Baltic Sea. Hence, positive effects for offshore wind power generation dominate there (cf. Fig, Fig).

4. Conclusion

We extended the series of climate impact studies on wind energy by means of further statistical features of wind velocities in Europe. Previous studies found that (strong) climate change has only a limited effect on average wind power yields [14-19]. But it is not enough to only consider average quantities. Therefore, we studied the probability and the persistence time of being in one of the three important regimes for wind power generation: r1 – no generation, r2 – highly fluctuating generation, and r3 – constant generation.

For most of continental Europe we find a shift from r2 to r1 under strong climate change, implying higher probabilities for wind turbines being idle. We further find a shift from r3 to r2 and r1 over the Atlantic Ocean and the Mediterranean Sea, which may be important for future, innovative offshore wind farms located in the deep sea. The persistence time of being in regime r1 is hardly affected – except for Sweden, Finland and Estonia where we find an increasing persistence time and thus a high probability for low wind power generation. Complementary results are found for the Baltic Sea, the Aegean Sea and the Strait of Gibraltar where the probability and the persistence time of being in regime r3 increase. Thus, it may be favorable to install offshore wind farms in these regions.

Considering the seasonal wind variability, we can enhance the findings of previous studies [9, 16, 17] where a relative increase over Central and North-Western Europe is found. This may increase power generation and possibly curtailment in the winter months and increase backup power needs due to low power output in the summer months.

There are hints for a much stronger impact of climate change in other regions of the Earth [26], but the temporal and spatial resolution of currently available climate projections is not sufficient for a detailed assessment. Thus, there is a need for more highly resolved wind data for further regions in the world. Additionally, it would be highly favorable if wind speeds at different heights close to the typical turbine hub height would be made available in future regional climate projections. This is important as it is not possible to include potential variations in the stability of the atmosphere and in the surface roughness into the analysis when using a power law to scale up wind velocities.

Acknowledgments

We acknowledge the World Climate Research Programme's Working Group on Regional Climate, and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. We also thank the climate modelling groups for producing and making available their model output. We also acknowledge the Earth System Grid Federation infrastructure an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP).

We gratefully acknowledge support from the Helmholtz Association (via the joint initiative “Energy System 2050 – A Contribution of the Research Field Energy”' and the grant no. VH-NG-1025) and the Federal Ministry for Education and Research (BMBF grant no. 03SF0472) to D.W..

References

[1] UNFCCC, Adoption of the Paris Agreement. Report No. FCCC/CP/2015/L.9/Rev.1, (2015).
[2] J. Rogelj, M. Den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, M. Meinshausen, Paris Agreement climate proposals need a boost to keep warming well below 2 C, Nature, 534 (2016) 631.

[3] M.Z. Jacobson, M.A. Delucchi, Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials, Energy policy, 39 (2011) 1154-1169.
[4] R. Sims, P. Mercado, W. Krewitt, G. Bhuyan, D. Flynn, H. Holttinen, G. Jannuzzi, S. Khennas, Y. Liu, L.J. Nilsson, Integration of renewable energy into present and future energy systems, IPCC special report on renewable energy sources and climate change mitigation, (2011).
[5] H.C. Bloomfield, D.J. Brayshaw, L.C. Shaffrey, P.J. Coker, H. Thornton, Quantifying the increasing sensitivity of power systems to climate variability, Environmental Research Letters, 11 (2016) 124025.
[6] M.R. Davidson, D. Zhang, W. Xiong, X. Zhang, V.J. Karplus, Modelling the potential for wind energy integration on China's coal-heavy electricity grid, Nature Energy, 1 (2016) 16086.
[7] J. Olauson, M.N. Ayob, M. Bergkvist, N. Carpman, V. Castellucci, A. Goude, D. Lingfors, R. Waters, J. Widén, Net load variability in Nordic countries with a highly or fully renewable power system, Nature Energy, 1 (2016) 16175.
[8] M. Huber, D. Dimkova, T. Hamacher, Integration of wind and solar power in Europe: Assessment of flexibility requirements, Energy, 69 (2014) 236-246.
[9] J. Weber, J. Wohland, M. Reyers, J. Moemken, C. Hoppe, J.G. Pinto, D. Witthaut, Impact of climate change on backup energy and storage needs in wind-dominated power systems in Europe, arXiv preprint arXiv:1711.05569, (2017).
[10] J. Weber, C. Zachow, D. Witthaut, Modeling long correlation times using additive binary Markov chains: applications to wind generation time series, arXiv preprint arXiv:1711.03294, (2017).
[11] J. Wohland, M. Reyers, J. Weber, D. Witthaut, More homogeneous wind conditions under strong climate change decrease the potential for inter-state balancing of electricity in Europe, Earth System Dynamics, 8 (2017) 1047.
[12] I. Staffell, S. Pfenninger, The increasing impact of weather on electricity supply and demand, Energy, 145 (2018) 65-78.
[13] B. Schäfer, C. Beck, K. Aihara, D. Witthaut, M. Timme, Non-Gaussian power grid frequency fluctuations characterized by Lévy-stable laws and superstatistics, Nature Energy, (2018) 1.
[14] H. Hueging, R. Haas, K. Born, D. Jacob, J.G. Pinto, Regional changes in wind energy potential over Europe using regional climate model ensemble projections, Journal of Applied Meteorology and Climatology, 52 (2013) 903-917.
[15] M. Reyers, J.G. Pinto, J. Moemken, Statistical–dynamical downscaling for wind energy potentials: evaluation and applications to decadal hindcasts and climate change projections, International Journal of Climatology, 35 (2015) 229-244.
[16] M. Reyers, J. Moemken, J.G. Pinto, Future changes of wind energy potentials over Europe in a large CMIP5 multi-model ensemble, International Journal of Climatology, 36 (2016) 783-796.
[17] J. Moemken, M. Reyers, H. Feldmann, J.G. Pinto, Wind speed and wind energy potentials in EURO-CORDEX ensemble simulations: evaluation and future changes, (submitted), (2018).
[18] I. Tobin, R. Vautard, I. Balog, F.-M. Bréon, S. Jerez, P.M. Ruti, F. Thais, M. Vrac, P. Yiou, Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections, Climatic Change, 128 (2015) 99-112.
[19] I. Tobin, S. Jerez, R. Vautard, F. Thais, E. van Meijgaard, A. Prein, M. Déqué, S. Kotlarski, C.F. Maule, G. Nikulin, Climate change impacts on the power generation potential of a European mid-century wind farms scenario, Environmental Research Letters, 11 (2016) 034013.
[20] D.P. Van Vuuren, J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, The representative concentration pathways: an overview, Climatic change, 109 (2011) 5.
[21] D. Jacob, J. Petersen, B. Eggert, A. Alias, O.B. Christensen, L.M. Bouwer, A. Braun, A. Colette, M. Déqué, G. Georgievski, EURO-CORDEX: new high-resolution climate change projections for European impact research, Regional environmental change, 14 (2014) 563-578.
[22] F. Giorgi, W.J. Gutowski Jr, Regional dynamical downscaling and the CORDEX initiative, Annual Review of Environment and Resources, 40 (2015).
[23] P. Samuelsson, C.G. Jones, U. Willén, A. Ullerstig, S. Gollvik, U. Hansson, C. Jansson, E. Kjellström, G. Nikulin, K. Wyser, The Rossby Centre Regional Climate model RCA3: model description and performance, Tellus A, 63 (2011) 4-23.
[24] G. Strandberg, L. Bärring, U. Hansson, C. Jansson, C. Jones, E. Kjellström, M. Kupiainen, G. Nikulin, P. Samuelsson, A. Ullerstig, CORDEX scenarios for Europe from the Rossby Centre regional climate model RCA4, SMHI, 2015.
[25] J. Manwell, J. McGowan, A. Rogers, Wind Energy Applications, Wind Energy Explained: Theory, Design and Application, Second Edition, 449-504.
[26] K.B. Karnauskas, J.K. Lundquist, L. Zhang, Southward shift of the global wind energy resource under high carbon dioxide emissions, Nature Geoscience, 11 (2018) 38.