Renewable Energy 145 (2020) 1306–1316

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Impacts of climate change on wind energy power – Four wind farms in Spain

Kepa Solaun [a, b, *], Emilio Cerdá [c]

[a] School of Sciences, Universidad de Navarra, Campus Universitario, 31080, Pamplona, Spain
[b] Factor CO_2, Colón de Larreátegui, 26, Planta 1, 48009, Bilbao, Spain
[c] Instituto Complutense de Estudios Internacionales (ICEI), Universidad Complutense de Madrid, Campus de Somosaguas, Pozuelo de Alarcón, 28223, Madrid, Spain

ARTICLE INFO

Article history:
Received 26 June 2018
Received in revised form
23 April 2019
Accepted 21 June 2019
Available online 22 June 2019

Keywords:
Climate change
Climate change adaptation
Wind energy
Energy economics

ABSTRACT

There is a growing interest on how climate change may affect the energy sector, including changes in wind energy generation. This paper builds on existing research adding an economic component that considers how climate change can affect operating margins and investment values in specific wind farms in Spain. A projection of wind speed was carried out using an ensemble of three climate models, two scenarios (RCP 4.5 and 8.5) and two time periods (2018–2041 and 2042–2065) per plant. Using historical power curves, the changes in wind speed were converted to production output. The results show variations in production of up to 8% and changes in operating margins up to 10%. Seasonal generation may fluctuate as well, with an increase in summer and decrease in winter. An investment analysis was also conducted to consider how climate change may influence future developments in the sector.

1. Introduction

Renewable energies are increasingly important in the energy mix of many countries. In particular, global wind energy generation has grown by more than 20% per year over the last nine years [1]. Given that half of the world's wind power capacity has been added in just the last five years, and it is now the most important source of new power generating capacity in Europe and the United States [2], it is essential to understand which variables may impact its performance. It should also be highlighted that wind energy plays a very important role in climate change mitigation, which has become a priority for the international community [3].

Climate change itself poses a potential risk for wind electricity production, as a changing climate may alter atmospheric dynamics and affect wind patterns [4]. Therefore, it is more important than ever to evaluate the impacts of future climate change scenarios on wind speed and other variables that might affect wind production, as they are a potential high risk for investors [5]. Wind turbines are increasing not only in capacity, but size as well, making them even more vulnerable.

Wind speed is the most important driver of wind energy that can be affected by climate change [6], however there is less research on aspects such as extreme wind events and gusts, icing of the blades, sea ice, permafrost or air density. Changes in these elements depend on variables that are much more difficult to predict [7].

Over the last decade, a vast number of studies have been carried out to forecast long-term wind patterns in the context of climate change. Most of this studies have been focused on developed countries, especially in the US [5,8–11]. In the last years, a few developing countries have been taken into consideration as well [12–16]. Most of these studies project a decrease in wind speed in the future [4]. However, most of the studies suggest that it is unlikely that mean wind speeds and energy density will change more than the inter-annual variability [7].

With respect to Europe, most studies project an increase in wind speed in the north and a decrease in the south, specifically in the Mediterranean, however these variations do not exceed magnitudes of 10–20% [17–22]. These predicted changes are usually more intense in scenarios with a higher concentration of greenhouse gases in the atmosphere [6,17,22].

---

* Corresponding author. School of Sciences, Universidad de Navarra, Campus Universitario, 31080, Pamplona, Spain.
E-mail addresses: ksolaun@factorco2.com (K. Solaun), ecerdate@ccee.ucm.es (E. Cerdá).

https://doi.org/10.1016/j.renene.2019.06.129
0960-1481/

Table 1
Characteristics of the analyzed plants. Source: ACCIONA.

Wind farm	Region	Beginning of operations by Acciona	Total power (MW)	Turbines (number)	Power (average kW per turbine)	Turbine type
AEGA (Cuadramón)	Galicia	1999	18.75	25	750	Neg Micon NM44/750
El Perdón	Navarre	1994 (renovated and expanded in 1995 and 1996)	20	40	500	Gamesa G42/600, V42 and V39 (500)
Río Almodóvar	Andalusia	2009 (previously since 2004)	12.8	16	800	MADE AE 56
Rubió	Catalonia	2005	49.5	33	1500	Acciona AW 1500/77

Therefore, the Mediterranean region usually faces the biggest changes, and Spain and Portugal are the countries whose energy system will be most severely affected by climate change, all technologies considered [23]. Regarding wind power output in Spain, a long-term assessment throughout the 20th century showed a decrease in Central Spain, versus an increase in the Gibraltar Strait area [24]. When it comes to future projections, one study analyzed changes in mean wind speed in eleven representative clusters across Spain, forecasting moderate reductions for all, but never greater than 3% [25]. Another more detailed assessment, including seasonal variations, also projected a reduction in wind power, with the exception of some areas in Southern Andalusia and the Gibraltar Strait region [26]. The general decreasing trend is consistent with projections for offshore wind with an expected reduction of less than 5% in most areas [27].

There is a lack of studies that provide an economic assessment on the consequences of these changes, even if some papers project impacts on electricity prices [28,29]. This gap can also be found in other renewable sources of generation [30,31].

The goal of this paper is twofold. On the one hand, an analysis was conducted to determine whether expected changes in wind speed may substantially affect electricity production at selected wind farms in Spain. On the other hand, an economic assessment has focused on how this would affect operating margins and investments in the sector, particularly in the context of a new regulatory regime in Spain that is reducing public subsidies on renewable energies. The study looked at four wind farms in Spain owned and operated by the company Acciona.

Accordingly, the paper is structured as follows: section 2 gives an overview of the methodology, including a description of the plants and any economic assumptions. Section 3 summarizes the results of the projection in terms of wind speed, production and seasonality. Section 4 analyzes the economic impact on operating margins and investment parameters. Sections 5 focuses on the discussion of the methodology and results. Finally, the paper closes with some concluding remarks.

2. Methodology

2.1. Description of the plants

As previously noted, this paper analyzes the impact of climate change on four wind farms. The farms were chosen among more than 200 that are currently managed by the company Acciona, due to their operating and technical features. The final goal is to apply the conclusions made here to other plants. Table 1 summarizes the most important characteristics of the plants.

Location was a very important variable in the selection as well. The wind farms are located far from each other (as shown in Fig. 1) and in representative areas that allow for some comparison with existing literature on wind resources in Spain [25,26]. Therefore, the sensitivity of the plants can be tested against other relevant sources of information.

Fig. 1. Location of the wind farms. Source: own elaboration.

Establishing an extended historical record for projecting wind speed is usually a challenge, as most wind farms have not been in operation for long periods of time [24,32]. In this case, Acciona provided hourly information on wind speed, temperature and active power for each of the plants for the period 2010–2016[1] (reference period). As the information was generated by several metering devices, with some gaps, 1.8% of historical registers were corrected. Additionally, a reanalysis of wind speed was conducted by Acciona, extending historical records back to 1987 with simulated data, as will be explained in section 3.2.

2.2. Methodological outline for the projections

Projections of surface wind speed depend critically on the assessment methods used. In fact, these projections may very well be more dependent on methodology than other climate variables, such as temperature or pressure [5]. Changes in wind production do not depend only on changes in wind velocity, but also on wind shear or wind velocity distributions [14]. However, climate models do not provide information for these other factors and, therefore, wind speed is the only changing variable in the probability density function considered in this paper.

Wind power is very sensitive to any change in wind speed, as the wind power flux is proportional to the cube of the speed [4–7] among others).

---

[1] Except for Rio Almodóvar, where active power was only available after 2011.

$$\boldsymbol{Pflux} = 1/2 \cdot \boldsymbol{\rho} \cdot \boldsymbol{U}^3$$

where Pflux is the wind power flux (or wind energy density), U is the wind speed and ρ is the air density.

The methodology used in this paper to project production can be summarized in five steps.

A) Ex post power curves.

To model the sensitivity of production to wind speed several alternative methods were considered: econometric methodologies (linear and polynomial regressions) and technical methods (manufacturer power curves and ex post power curves). Ex post curves were built by calculating the average hourly active power for each wind speed during the seven years of the reference period (using bins with a 0.5 m/sec resolution). The ex post curves showed a better correlation with historial data than any other method across all wind farms (95% in Río Almodóvar, 93% in Cuadramón and Rubió and 87% in El Perdón) as well as limited differences in absolute figures (always less than ± 0.6%).

For a given farm, consider the following hourly data provided by Acciona:

$$(x_i, y_i), \text{ for } i = 1, 2, \ldots, I,$$

where x_i is the wind speed (in m/sec) and y_i is the active power (in MW) at time i.

Let $[0, v_{\max}]$ be the interval of possible values of the wind speed. In this interval a partition is defined in the following way:

$$[0, 0.5), [0.5, 1), [1, 1.5), \ldots, [v_{k-1}, v_k), \ldots, [v_{K-2}, v_{K-1}), [v_{K-1}, v_K],$$

where $v_0 = 0$, $v_K = v_{\max}$, $v_K - v_{K-1} \le 0.5$, and $v_k = v_{k-1} + 0.5$, for $k = 1, 2, \ldots, K-1$.

Consider then the bins B_k, where $B_k = [v_{k-1}, v_k)$, for $k = 1, 2, \ldots, K-1$, and $B_K = [v_{K-1}, v_K]$

For each (x_i, y_i), allocate $(x_i, y_i)$to bin B_k, such that $x_i \in B_k$.

Define $\tilde{y}_i$ as the mean value of the quantities y_r which belong to bin B_k.

The ex post curve is constructed from $(x_i, \tilde{y}_i)$, for $i = 1, 2, \ldots, I$.

The correlation between $\{y_i\}_{i=1,\ldots,I}$ and $\{\tilde{y}_i\}_{i=1,\ldots,I}$ is calculated.

B) Projections.

The ex post curves were later used to ascertain production under future climate change scenarios. To do so, the results from EURO-CORDEX (regional climate model inter-comparison project [33], 11 global climate models) through the Copernicus tool, which provides wind speed data and projections at heights of 10 m for each wind farm until 2065 (12 km × 12 km resolution). Two Representative Concentration Pathways (RCP) developed for the 5th Assessment Report of the Intergovernmental Panel on Climate Change were used: RCP 4.5 and RCP 8.5 [34,35]. Despite the uncertainties of global climate models, they are the most well-trusted source for projections [16]. For each farm, an ensemble was established using an average of the three models that showed the best correlation with historical data, as it is explained next.

Consider the hourly data

$$\{x_i\}, \text{ for } i = 1, \ldots, I,$$

corresponding to the wind speed at turbine hub height H.

Now, the grid in which the wind farm is located in the EURO-CORDEX initiative (with 11 global climate models) has to be obtained. For each of the 11 models, the wind speeds for year and season are taken form EURO-CORDEX:

For each model M_l, $l = 1, \ldots, 11$,

$$\{v_j^l\}_{j=1,\ldots,28}$$

are the past wind speeds for years 2010–2016, given by the EURO-CORDEX initiative for the grid in which the wind farm is located, where j = 1 corresponds to the season (December 2009, January and February 2010), j = 2 to (March, April, May 2010), j = 3 to (June, July, August 2010), j = 4 to (September, October, November 2010), j = 5 to (December 2010, January, February 2011), …, j = 28 to (September, October, November 2016).

From the data $\{x_i\}_{i=1,\ldots,I}$ the values $\{x_j^m\}_{j=1,\ldots28}$ are obtained where x_j^m is the mean value of x_i belonging to season $j \in \{1, \ldots, 28\}$.

For each model $l \in \{1, \ldots, 11\}$, the correlation between $\{v_j^l\}_{j=1,\ldots,28}$and $\{x_j^m\}_{j=1,\ldots28}$ is calculated.

The three global climate models for which such correlation is higher are selected.

Define $\{v_j\}_{j=1,\ldots,28}$, where v_j is the mean value of the speeds v_j^l, among the three models which have been selected.

Using the EURO-CORDEX simulations, from the past wind speeds $\{v_j\}_{j=1,\ldots,28}$, the projections of wind speeds for the future $\{w_f\}_{f=1,\ldots,F}$ are obtained, where $f = 1$ is the season DecJanFeb2018, $f = 2$ is MarAprMay 2018, $f = 3$ is JunJulAug 2018, $f = 4$ is SepOctNov 2018, …, $f = F$ is SepOctNov 2065 (in fact, $F = 192$), for each of the two RCPs (4.5 and 8.5), where the average for the three selected models has been included in each of the values corresponding to the future.

C) Vertical extrapolation.

The speed data and projections provided by EURO-CORDEX are given for heights of 10 m, therefore these data have to be transformed for heights of H meters, using the formula

$UH = US\left(\frac{H}{10}\right)^{\alpha}$, [17,24] among others, where UH is the wind speed at turbine height H, US is the wind speed at 10 m and α is an ad-hoc parameter that denotes the contribution of the site roughness for the speed vertical gradient of the atmospheric boundary layer. The ad-hoc value of α is calculated as follows: take the values $\{x_j^m\}_{j=1,\ldots28}$, at height H, and the values $\{v_j\}_{j=1,\ldots,28}$, at height 10, α is taken as the constant value in order that these two series are as close as possible.

D) Downscaling.

For the projection, a statistical downscaling was performed using the Delta Method [14,36], as explained next.

Consider the past wind speeds $\{v_j\}_{j=1,\ldots,28}$, corresponding to each of the seasons for years 2010–2016. For each season, the mean value is calculated in accordance with the following expressions:

$$v_s^m = \frac{1}{7}\sum_{r=0}^{6} v_{s+4r}, \text{ for } s = 1, 2, 3, 4$$

where s = 1 is the season DecJanFeb, s = 2 corresponds to MarAprMay, s = 3 is JunJulAug and s = 4 is the season SepOctNov.

Therefore, the following mean values corresponding to each season in the past are obtained $\{v_s^m\}_{s=1,2,3,4}$.

On the other hand, for each of the two RCPs (4.5 and 8.5), the values corresponding to each future season are obtained from 2018 to 2065 $\{w_f\}_{f=1,\ldots,F}$.

Now the time series $\{v_s^m\}_{s=1,2,3,4}$and $\{w_f\}_{f=1,\ldots,F}$ are compared in the following way:

Calculate the following differences, for $f = 1, \ldots, F$, :

$$d_1 = w_1 - v_1^m, \quad d_2 = w_2 - v_2^m, \quad d_3 = w_3 - v_3^m,$$
$$d_4 = w_4 - v_4^m, \quad d_5 = w_5 - v_1^m, \quad d_6 = w_6 - v_2^m,$$

$$d_7 = w_7 - v_3^m, \quad d_8 = w_1 - v_4^m, \ldots.$$

that is:

$$d_f = \begin{cases} w_f - v_1^m, & \text{if} \quad f+3 \text{ is a multiple of } 4, \\ w_f - v_2^m, & \text{if} \quad f+2 \text{ is a multiple of } 4, \\ w_f - v_3^m, & \text{if} \quad f+1 \text{ is a multiple of } 4, \\ w_f - v_4^m, & \text{if} \quad f \text{ is a multiple of } 4. \end{cases}$$

The respective variations from the past to the future, expressed on a per unit basis are the following:

$$D_f = \begin{cases} d_f \big/ v_1^m, & \text{if } f+3 \text{ is a multiple of } 4, \\ d_f \big/ v_2^m, & \text{if } f+2 \text{ is a multiple of } 4, \\ d_f \big/ v_3^m, & \text{if } f+1 \text{ is a multiple of } 4, \\ d_f \big/ v_4^m, & \text{if } f \text{ is a multiple of } 4. \end{cases}$$

E) Representative year and production projection.

Rather than calculating the average wind speed per hour in the reference period, for each plant a representative year was established in terms of production and wind. This is to account for the non-linear relationship between wind speed and production in the first part of the power curve (where most registers are located), and therefore average wind does not represent average production.

Take the hourly data provided by Acciona

(x_i, y_i), for $i = 1, 2, \ldots, I$.

Define the mean value of the active power corresponding to each of the years from 2010 to 2016, in the following way:

$$Y_1 = \sum_{i \in year2010} y_i, \quad Y_2 = \sum_{i \in year2011} y_i, \quad \ldots \quad , \quad Y_7 = \sum_{i \in year2016} y_i$$

Define the annual mean production corresponding to the years 2010–2016 as $\overline{Y} = \frac{1}{7}\sum_{n=1}^{7} Y_n$.

The year n^* is chosen which solves the problem:

$\min\limits_{n \in \{1,\ldots,7\}} |Y_n - \overline{Y}| \Rightarrow n^*$ is the representative year.

Now, take all the hourly data corresponding to year n^*, $\{(x_i, y_i)\}_{i \in year\ n^*}$.

Now the values x_i corresponding to year n^* are slightly modified (multiplied by a constant), to solve for $|Y_{n^*} - \overline{Y}| = 0$, passing x_i through the ex post curve satisfying the condition $\sum\limits_i \hat{y}_i = \overline{Y}$. $\{\hat{x}_i\}_{i \in year\ n^*}$ are these (slightly) modified values, and their corresponding quantities in the ex post curves are $\hat{\hat{y}}_i$, with $\sum\limits_i \hat{\hat{y}}_i = \overline{Y}$.

Therefore, the data $\{(\hat{x}_i, \hat{\hat{y}}_i)\}_{i \in year\ n^*}$ is obtained

The values $\hat{x}_i$, corresponding to the year n^* are classified for each of the seasons $s = 1, 2, 3, 4$ and for each season the mean value is obtained. Therefore, the following mean values corresponding to each season in the past are $\{X_s\}_{s=1,2,3,4}$.

For each of the two RCPs (4.5 and 8.5) the wind speed corresponding to each season of the future $\{XF_f\}_{f=1,\ldots,F}$, is obtained using the differences previously gathered:

$$XF_f = \begin{cases} X_1\left(1 + D_f\right), & \text{if} \quad f+3 \text{ is a multiple of } 4, \\ X_2\left(1 + D_f\right), & \text{if} \quad f+2 \text{ is a multiple of } 4, \\ X_3\left(1 + D_f\right), & \text{if} \quad f+1 \text{ is a multiple of } 4, \\ X_4\left(1 + D_f\right), & \text{if} \quad f \text{ is a multiple of } 4. \end{cases}$$

The variations obtained from the climate models per year and season were later applied to each hourly register of the representative year, providing a wind projection for the years 2018–2065. This was then transformed into production using the above-mentioned ex post curves.

2.3. Methodological outline for the economic analysis

Investment costs of onshore wind energy have dropped since the 1980s due to economies of scale. While the rated capacity of new turbines has increased, the unitary cost (labour and materials) has remained constant, or even decreased [37]. Despite a change in tendency between 2004 and 2010, mainly due to the higher cost of commodities, prices seem to have stabilized since then [38]. Operation and maintenance costs have decreased over time as well, both because of economies of scale and because newer turbines require less maintenance [39].

The analysis carried out for this paper was focused on operating margins. Official sources of information were used as the baseline scenario, both for income and costs. It allowed to test whether wind generation will be affected by climate change in the specific context of the current regulatory framework and incentives. However, cost parameters provided by Acciona for each of the wind farms were used as well and will be presented in a separate analysis.

Operating margins are calculated as follows:

$$OM = \frac{ES + IS - CAPEX - OPEX - T}{ES + IS}$$

where:

OM is the *operating margins* of each wind farm.

ES is *energy sales*, which considers the product of energy sold in the market and the *adjusted price* (AP) that will be explained below.

IS refers to the *Investment subsidy* that some plants can receive during their regulatory time span.

CAPEX is the *capital expenditure.*

OPEX is the *operating expenses.*

T refers to *taxes.*

When calculating ES, the chosen reference for the price of electricity is that set by the Spanish Government in Order 1045/2014, which assumes an average market price of 52 €/MWh from 2017 onwards. This reference was confirmed by Order ETU/130/2017. The price was adjusted as shown in the following equation:

$$AP = RP \cdot SD \cdot AR$$

where:

AP is the *adjusted price.*

RP is the above-mentioned *reference price* (52 €/MWh).

SD is the historical *seasonal deviation* from the *reference price.* This variable calculates the average deviation of prices in each month from the average price of each year. This variable will

Table 2
Results for the adjusted price (AP), seasonal deviation (SD) and alignment ratio (AR). Source: Own elaboration based on data from Red Eléctrica Española and Operador del Mercado Ibérico de Energía (OMIE).

Variables	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Reference Price	52	52	52	52	52	52	52	52	52	52	52	52
Weighted monthly average electricity price for wind	40.8	35.3	33.6	32.7	39.4	44.8	48.1	47.8	49.1	47.3	42.9	45.1
Alignment ratio	87%	84%	87%	88%	93%	95%	97%	97%	94%	93%	91%	91%
Seasonal deviation	102%	90%	83%	80%	92%	103%	108%	107%	113%	111%	103%	109%
Adjusted price	46.0	39.3	37.5	36.6	44.5	50.8	54.2	53.8	55.6	53.7	48.7	51.6

Table 3
CAPEX and OPEX values from literature (closest values to Spain have been included when available). Source: own elaboration.

Source	CAPEX	OPEX
Blanco 2009 [39]	1100-1400 €/kW	1.2–1.5 cent€/kWh
De Jaeger et al. *2011* [37]	<1125–1525 €/kW	35-45 €/(kW*year)
IRENA, 2012 [38]	1882 USD/kW	2.7 cUSD/kWh
EWEA, 2009 [41]	1227 €/kW	1.2–1.5 c€/kWh
WindFacts, 2009 [42]	1200 €/kW	1.2–1.5 c€/kWh
IDAE- Boston Consulting Group, 2011 [43]	1000-1300 €/kW	1.72–2.16 c€/kWh
IDAE- R. Berger, 2014 [40]	1370-1550 €/kW	41.3 €/(kW*year)

become relevant as the projections change the distribution of production throughout the year.

AR is the *alignment ratio*, which calculates how the weighted monthly average electricity price for wind in one month differs from the average price in the market for that month. Due to its lack of flexibility, wind electricity is on average sold at a lower price than the market average.

We used the above formula to calculate the adjusted price from hourly data from the Spanish Electricity market from 2008 to 2016. Results are shown in Table 2.

Regarding the IS, it is important to highlight that the legal transition in Spain on renewable energies has a substantial impact on the calculations. The remuneration system has changed substantially since 2012. According to Royal Decree 413/2014, wind farms can receive public financial support during their first 20 years of operation. In this particular case, two wind farms (Cuadramón, El Perdón) have exceeded that time and therefore are only funded through electricity sales. The other two (Rubió and Río Almodóvar) will still receive an investment subsidy (“Retribución a la inversion”) until that time is over. As the goal of the paper is to focus on specific climate change impacts and not to address financial implications of the new regulatory regime, and because of the long time-frame considered, baseline calculations assume that the investment subsidy is no longer in place. However, due to impact of removing it, calculations have also been made considering its continuation and results will be shown as an alternative scenario.

Regarding CAPEX and OPEX, several studies were evaluated, as shown in Table 3. For the official sources, an analysis commissioned by the Spanish Government [40] was chosen as the main reference, as it specifically addresses data from Spain, and has been used as a legal reference in the reform of the Spanish electricity market for renewable energies.

When calculating the CAPEX, the cost of civil works and engineering was omitted, as these plants are already in operation. Therefore, the analysis only considered the investment required to replace the wind turbines. This equipment was assigned a physical lifespan of 25 years, based on the experience of the company.

The OPEX considers operations and maintenance, management, rental, insurances, electricity and self-consumption. Values provided by Acciona were aggregated as fixed operational costs, variable operational costs and representation costs.

National taxes (electricity generation and access tax) were considered, as well as regional taxes that exist in some regions. Local taxes on economic activities and property were not taken into account, and neither were taxes that are neutral to producers (such as the Added Value Tax or the Special Tax on Electricity).

For both incomes and costs, a ceteris paribus approach was used, so that unitary costs and electricity prices are constant over time. This method is intended to maintain a focus on the singular goal of the paper, which is to quantify the impact of climate change on wind electricity, not to forecast electricity prices or evolution of costs. Said variables may change substantially over the time range of the projections(2018–2065) therefore complicating an assessment of the specific variable being quantified, as explained in a previous paper [31].

Likewise, the physical characteristics of the farms was assumed to remain constant, with no adaptation measures.

3. Projection

3.1. Results

Historical average wind speed is shown in Table 4, together with expected changes in the average for both RCPs. A decline is expected in Cuadramón and Rubió, and this decrease intensifies with time (near future versus mid century). Río Almodóvar shows increases in average wind speed, while in El Perdón both reductions and increases are seen. In almost all cases, there is a greater variation from the historical average under scenarios with higher concentrations of greenhouse gases in the atmosphere (RCP 8.5 compared to RCP 4.5), which is consistent with literature [6].

With regards to production, as expected, trends are consistent with those seen for wind speed, however they are more pronounced. Table 5 compares historical average production with the annual average projected per farm. Production declines under all scenarios and future periods in Cuadramón and Rubió and increases in Río Almodóvar. El Perdón does not show a uniform trend; instead the evolution depends on the scenarios and future periods considered. The magnitude of the change is consistent with other case studies in literature, as explained above.

Some studies highlight that the changing climate may affect intra-annual variability of wind generation, therefore limiting its reliability and predictability as a power source [6]. This variability was considered in the study, taking into account its potential

Table 4
Historical average wind speed versus medium and long-term projections. Source: own elaboration.

Wind farm	RCP	Historical average (m/sec)	Average hourly variation (near future, 2018–2041)	Average hourly variation (mid century, 2042–2065)
Cuadramón	4.5	7.07	−3.5%	−3.6%
	8.5	7.07	−4.0%	−4.9%
El Perdón	4.5	9.32	−0.1%	1.5%
	8.5	9.32	1.0%	0.2%
Río Almodóvar	4.5	6.21	1.2%	2.9%
	8.5	6.21	2.5%	3.9%
Rubió	4.5	5.69	−0.7%	−4.2%
	8.5	5.69	−1.2%	−4.1%

economic and operational implications. Fig. 2 shows seasonal variations between the reference period and future scenarios (an average of RCPs 4.5 and 8.5). A decline in production is expected in the winter and an increase in summer for all plants. Seasonal variations are most relevant at Rubió, with a very stark reduction in spring and increase in autumn. This change will become relevant in the economic analysis as the adjusted price is on average higher during summer and autumn. Rubió, for instance, will benefit from this fact according to the projections. The standard deviation of changes in wind speed throughout the different periods was analyzed, but no clear trend has been found in this regard.

3.2. Context in literature

In order to evaluate the accuracy of the results, other sources of information were considered. On the one hand, some general projections of wind speed variations for Spain from existing literature were analyzed, although they cover large areas of the country rather than specific locations, as in this paper. There are no projections of electricity production, however there is a high correlation between wind speed and production, as shown above. On the other hand, a climate reanalysis was conducted in order to generate a historical series of wind speeds for each of the farms.

The results of this paper are compatible with trends shown in a study of projected changes in wind energy potentials in Iberia [26], despite some differences in timeframes (2041–2070 vs. 2042–2065 in this study) and variables (wind energy power vs. wind speed). The trend is consistent in terms of both increases (El Perdón, Río Almóvar) and decreases (Rubió, Cuadra) in average wind speed. The magnitude of these variations is also consistent and becomes more pronounced over time (from better to worse: Río Almodóvar, El Perdón, Cuadramón, Rubió).

A broad study of wind speed variability and future changes in the peninsula and Balearic Islands [25], reveals a decline in wind speed for all analysed clusters (2031–2050). Therefore, the results show the same tendency in Cuadramón and Rubió (although

Table 5
Historical average production versus medium and long-term projections. Source: own elaboration.

Wind farm	RCP	Historical average (MWh)	Average yearly variation (near future, 2018–2041)	Average yearly variation (mid century, 2042–2065)
Cuadramón	4.5	47,562	−4.7%	−4.5%
	8.5	47,562	−5.2%	−5.7%
El Perdón	4.5	65,508	−0.5%	1.9%
	8.5	65,508	1.0%	−0.1%
Río Almodóvar	4.5	21,728	2.3%	5.0%
	8.5	21,728	3.6%	6.5%
Rubió	4.5	88,581	−1.7%	−8.2%
	8.5	88,581	−2.5%	−8.0%

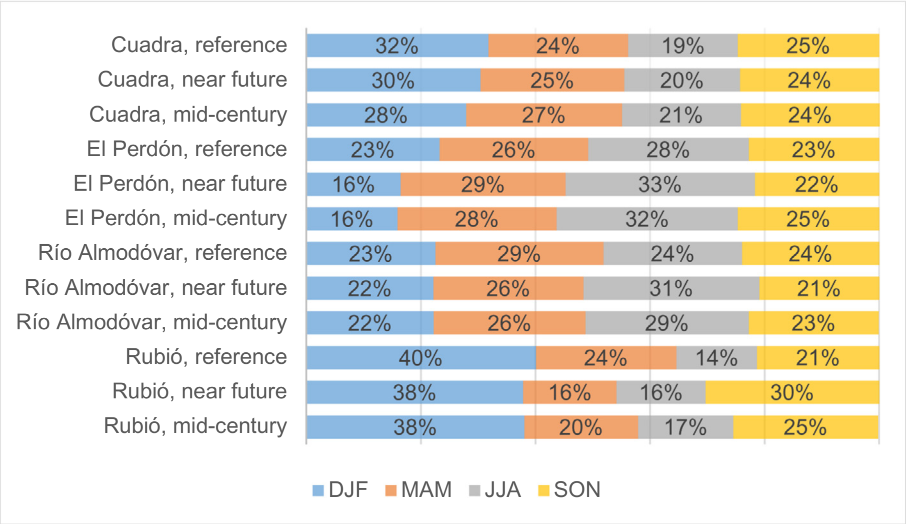


Fig. 2. Seasonal production (in %) by wind farm. Source: own elaboration.

changes are less significant than in this paper), and a contrary trend in Río Almodóvar and in some periods in El Perdón. However, the analysis was oriented towards providing aggregate data for the Iberian Peninsula and its whole territory was divided in only 11 clusters (in fact El Perdón and Rubió are included in the same one).

The general trends are also consistent with other studies that provide a general overview of future changes in Europe. Most papers on this topic project wind speed decrease in the Mediterranean area (Rubió) [6,17,19–22,44,45] and many of them project an increase in the Gibraltar Strait area (Río Almodóvar) by mid-century [17,19,22,44]. Regarding the Ebro Valley area (El Perdón), the trend is less consistent with only some papers projecting an increase [22,44].

The climate reanalysis was conducted by Acciona for each of the farms, extrapolating the hourly wind speed series from 2010 to 2016 (measured data) back to 1987 (CFSR[2]) and to 1997 (Merra2[3]) using Vortex Series. The reanalysis provides simulated data combining global circulation models (GCMs) with meteorological measurements [46]. It is a widely used method to simulate large series of wind data, but correlation needs to be validated first, as accuracy on literature depends on specific variables such as altitude [32].

In this case, the correlation between the data obtained from reanalysis and historical data for 2010–2016 ranges from 50% to 85% depending on the model and the wind farm (with the lowest average correlation in Cuadramón, and CFSR providing better correlation than Merra2 in all wind farms). As shown in Fig. 3, the reanalysis is not consistent in this farm, where historical data does not correspond with the reanalysis. The reanalysis does not provide projections, but as a larger dataset is available, a linear tendency has been calculated and extended for all farms. This is not a robust method to project wind speed but is useful for the operators of the plant as it shows whether the projections (RCP 4.5) are consistent with the historical trend, even if the time series are short. As shown in Fig. 3 for CFSR, the tendencies are consistent in three of the parks and differ in Rubió. In almost all cases the slope of the change is higher than in the projections.

4. Economic analysis

4.1. Analysis of operating margins

As we have assumed the removal of the investment subsidy as the baseline scenario, the results are very dependent on the production to power ratio (equivalent full load hours). There is a stark difference in performance between the four wind farms for this ratio, as shown in Table 6.

The historical operating margins are consistent with these figures, as seen in Table 7. The Adjusted Price (AP) has been used both for the reference period and for the projections considering the goal of this paper. When using official sources, Cuadramón and El Perdón have the highest operating margins (15% and 38% respectively), whereas Río Almodóvar and Rubio have negative values (−14% and −10% respectively).

With respect to future projections, operating margins do not change dramatically, except in Río Almodóvar, which experiences an increase in production and improves its margins over time, particularly in the RCP 8.5 (which is more beneficial in terms of production and seasonality). In Rubió, due to expected reductions in production by the mid-century, operating profits are also substantially affected, reaching -14-15%, depending on the RCP. In the near future, changes in seasonality have a positive impact on income and operating margins. Cuadramón shows positive values, but in a smaller magnitude than El Perdón, in part due to the impact of regional taxes.

When using cost parameters provided by Acciona (Table 8), there are some differences in the starting point, with improvements in Cuadramón and Rubió. The evolution in future periods follows a similar evolution than the one shown above.

As stated in the methodology section (2), an alternative scenario has been designed, assuming that Río Almodóvar and Rubió receive the public investment subsidy for the period set in the regulatory framework. This scenario is not the most appropriate one to notice the influence of climate change, as the subsidy has a huge impact on the results, but it offers an interesting insight on the impact of the removal of public incentives to utilize renewable energies, which is much bigger than the physical impacts of climate change. Considering this variable, Table 9 shows how these two farms decrease their operating margins over time once the subsidy has been removed.

As explained above, these results cannot be compared with other sources in literature, as existing studies rarely provide economic estimates and those that do, focus on a macro perspective, analyzing the impact on electricity prices [28,29], not on the perspective of the operator of the plant, that would be more interested in costs or operating margins.

4.2. Investment analysis

This analysis has been carried out regarding a hypothetical investment from scratch, taking into account all investments and the full set of capital costs. Therefore, civil works and engineering, as well as the full cost of the turbines will be included from the beginning. The investment subsidy has not been considered.

A period of 25 years has been considered (from 2018 to 2042), with a discount rate of 2%, consistent with other studies in the sector in Spain [31,47]. In one variation, there is no need for external funds and no opportunity costs have been included. In a second variation, financial costs have been added for 80% of the capital at a 6% discount rate under an equated yearly installment (equal payments during the loan life cycle to pay off interests and capital). The residual value in the last year accounts for the value of the initial investment excluding the cost of the turbines (civil works, electrical investment, land development and others).

The net present values for each wind farm, scenario and financing variation are shown in Table 10. The results are consistent with those of operating margins, with positive values for El Perdón and negative values for Río Almodóvar and Rubió. Cuadramón is closer to positive values (if the investment is done internally) and can achieve them if the lifetime of the turbines is extended beyond the 25 years. There is a clear difference in values when the financial costs are considered even if El Perdón remains with positive values. Rubió shows the worst results, in part due to its bigger size compared to the other wind farms.

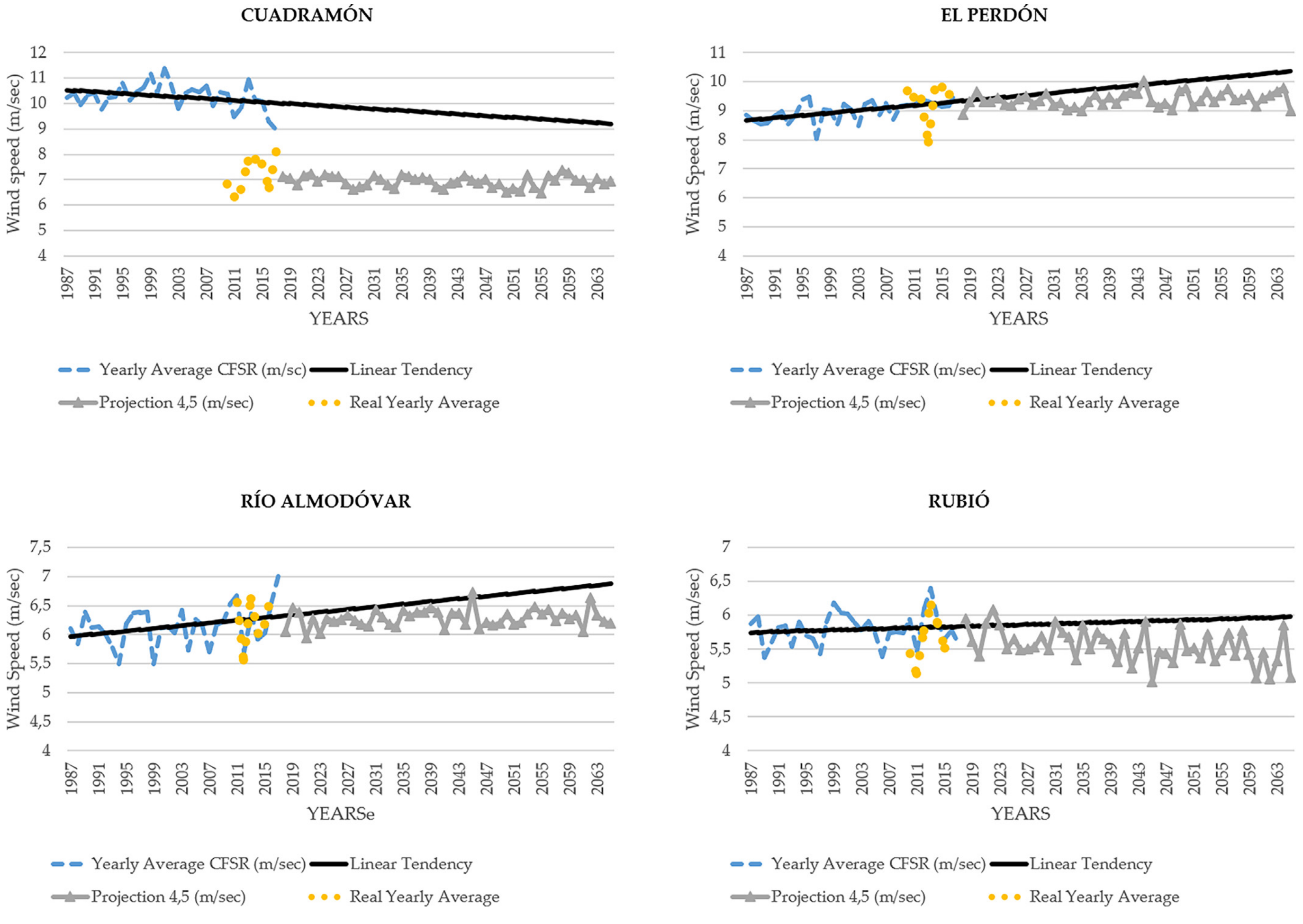
5. Discussion

This paper has analyzed the impact of changes in wind speed due to climate change in the long term. According to the results shown above, these changes will affect the production and operating margins of the selected wind farms. The projections were based on existing public information on future wind speed for two IPCC scenarios.

---

[2] Climate Forecast System Reanalysis, by the National Centers for Environmental Prediction (NCEP).

[3] Modern-Era Retrospective analysis for Research and Applications, Version 2, by NASA.


CUADRAMÓN

EL PERDÓN

RÍO ALMODÓVAR

RUBIÓ

Fig. 3. Reanalysis and projections. Source: Own elaboration based on data from Acciona.

Table 6
Full load hours at each wind farm. Source: own elaboration based on data from Acciona.

Wind farm	Period	Average annual production (MWh)	Installed capacity (MW)	Full load hours
Cuadramón	2010–2016	47,562	18.75	2537
El Perdón	2010–2016	65,508	20	3275
Río Almodóvar	2011–2016	21,728	12.8	1698
Rubió	2010–2016	88,581	49.5	1790

Table 7
Operating margins at each plant in the reference period and in the projections under official cost parameters. Source: own elaboration.

Wind farm	Historical average	RCP 4.5		RCP 8.5	
		Near future, 2018–2041	Mid century, 2042–2065	Near future, 2018–2041	Mid century, 2042–2065
Cuadramón	15%	12%	12%	12%	11%
El Perdón	38%	39%	40%	39%	39%
Río Almodóvar	−14%	−8%	−5%	−6%	−4%
Rubió	−10%	−8%	−15%	−8%	−14%

The results of the physical projections of this paper, as explained in section 3.2, are mostly consistent with other projections in this geographical area, both specific for the Iberian Peninsula and general for Europe. However, no studies have been conducted on the economic impacts of these changes from the perspective of the operator of the plant, so the results on operating margins and investment parameters cannot be compared with existing literature.

Due to the long-term framework of the assessment, certain methodological choices were made to avoid distortion. First, the analysis was based on operating margins rather than profits, to prevent the impact of discount rates. Second, a ceteris paribus

Table 8
Operating margins at each plant in the reference period and in the projections under cost parameters provided by Acciona. Source: own elaboration.

Wind farm	Historical average	RCP 4.5		RCP 8.5	
		Near future, 2018–2041	Mid century, 2042–2065	Near future, 2018–2041	Mid century, 2042–2065
Cuadramón	17%	15%	15%	14%	14%
El Perdón	26%	26%	26%	26%	26%
Río Almodóvar	−29%	−24%	−22%	−22%	−20%
Rubió	−3%	−1%	−6%	−2%	−5%

Table 9
Operating margins at each plant in the reference period and in the projections under official cost parameters. Source: own elaboration.

Wind farm	Historical average	RCP 4.5		RCP 8.5	
		Near future, 2018–2041	Mid century, 2042–2065	Near future, 2018–2041	Mid century, 2042–2065
Río Almodóvar	62%	31%	−5%	31%	−4%
Rubió	45%	14%	−15%	13%	−14%

Table 10
Net present values of investments in the wind farms. RCP 4.5 and 8.5. Source: own elaboration.

Wind farm	RCP 4.5		RCP 8.5	
	100% internal	80% external	100% internal	80% external
Cuadramón	−2,466,722	−8,048,294	−2,627,409	−8,208,981
El Perdón	15,428,652	9,474,975	16,053,846	10,100,169
Río Almodóvar	−6,722,617	−10,532,970	−6,436,118	−10,246,471
Rubió	−25,901,075	−40,636,425	−26,357,648	−41,092,999

approach was chosen for considering costs and incomes. This was done, as explained in a previous paper [31], to specifically highlight the impacts of climate change, which may be difficult to pinpoint when changes in costs and prices are considered over such a long period. This paper has also assumed that no adaptation measures will be undertaken. However changes in the design and operation of wind turbines are to be expected in the long term if changes in wind speed are confirmed over time [15].

Regarding the economic assumptions, this paper outlined two cost scenarios (official and company assumptions) and two income scenarios (with and without the investment subsidy). By doing so, it provides robustness to the results and a better understanding of the importance of the regulatory framework.

There are several uncertainties that could benefit from future research, such as the fact that only changes in wind speed have been considered here. Changes in wind direction and other variables such as extreme wind events or icing of the blades may be relevant as well [7].

The resolution of the bins for the power curves (0.5 m/sec) was based on existing information and is consistent with current practice in the sector, however this might underestimate the cumulative impact of small changes in wind speed.

6. Conclusions

This study has shown that climate change may affect wind speed and, therefore, wind production in Spain. Four wind farms were chosen for their characteristics and geographical locations, where existing literature suggests variations in the resource.

According to the results, changes in average wind speed vary between wind farms. A decrease in speed is to be expected in Cuadramón and Rubió for all scenarios and time periods. In Río Almodóvar, an increase is projected, whereas results for El Perdón depend on the time frame and scenario. The greatest decrease is projected for Rubió and Cuadramón, with reductions of around 5% for the period 2042–2065.

Regarding annual production, results are consistent with those for wind speed, but in a greater magnitude. Again, Rubió shows the most significant decrease in production, at around 8% for the period 2042–2065. Increases in Rio Almodóvar are projected to be between 5% and 6% for the same period. Concerning seasonality, projections show an increase in production at all plants during the summer, and a decline during the winter.

These changes in production affect the operating margins and investment parameters of the plants. Considering the economic assumptions made in this analysis, said parameters are highly influenced by the equivalent full load hours of the farms. The production to installed power ratio during the historical period in El Perdón (3275) is nearly double that of Río Almodóvar (1698), and therefore has a clear impact on calculated operating margins. Due to the expected increases in production, changes in operating margins are relevant in both Río Almodóvar and Rubió. Only slight changes are projected for the other plants.

These conclusions will benefit from further research and broadened information, as described in the section Discussion (5). More accurate projections that consider further climate variables will improve the quality of the results

With respect to conclusions related to public policy, this paper does not foresee dramatic changes in wind production at the analyzed plants. Changes in the regulatory framework have a higher impact on the analyzed plants, according to the calculations. As shown in the investment analysis, new farms such as Rubió and Río Almodóvar may not be profitable without the public investment subsidy.

In any case, wind energy generation is the most important source of renewable electricity in Spain [48], and the evolution of wind speed should be monitored to confirm the conclusions of existing climate projections.

Declarations of interest

None.

Author contributions

Both authors conceived and designed the model. Emilio Cerdá set the mathematical foundations for it. Kepa Solaun implemented the model and carried out the calculations for the case study. Kepa Solaun wrote the paper, which was subsequently thoroughly reviewed by Emilio Cerdá.

Acknowledgments

Financial support from the Spanish Ministry of Economy and Competitiveness (ECO2015-70349-P) is acknowledged. We deeply appreciate the valuable support from the ACCIONA staff (Magdalena García Mora, Júlia Lucena Betriu, Mikel Illarregi Anabitarte, Javier Ruiz Guillén, Tamara Méndez Farrero, Ignacio Oficialdegui López, Jorge Angulo Fernández). We are also grateful for the comments from the participants in the Seminar of the Interuniversity Phd Program on Economics of the University of Murcia (April 2018). Marina Arroyo and Octavio Jaume helped us with the geographical information and projections. Helen Poliquin and Christina Garcia reviewed the use of English in the manuscript. Iker Larrea and Itxaso Gómez provided relevant feedback.

References

[1] IRENA, Renewable Energy Statistics 2016, The International Renewable Energy Agency, Abu Dhabi, 2016. www.irena.org.

[2] J.L. Sawin, K. Seyboth, F. Sverrisson, Renewables, Global Status Report, REN21 Secretariat, Paris, France, 2016, ISBN 978-3-9818107-0-7, 2016.

[3] O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Eickemeier, P. Matschoss, G. Hansen, S. Kadner, S. Schlömer, T. Zwickel, C. Von Stechow, Summary for policymakers, in: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, 2011, IPCC, 2011, https://doi.org/10.5860/CHOICE.49-6309.

[4] S. Greene, M. Morrissey, S.E. Johnson, Wind climatology, climate change, and wind energy, Geogr. Compass. 4 (2010) 1592–1605, https://doi.org/10.1111/j.1749-8198.2010.00396.x.

[5] D.J. Rasmussen, T. Holloway, G.F. Nemet, Opportunities and challenges in assessing climate change impacts on wind energy—a critical comparison of wind speed projections in California, Environ. Res. Lett. 6 (2011), 024008, https://doi.org/10.1088/1748-9326/6/2/024008.

[6] D. Carvalho, A. Rocha, M. Gómez-Gesteira, C. Silva Santos, Potential impacts of climate change on European wind energy resource under the CMIP5 future climate projections, Renew. Energy 101 (2017) 29–40, https://doi.org/10.1016/j.renene.2016.08.036.

[7] S.C. Pryor, R.J. Barthelmie, Climate change impacts on wind energy: a review, Renew. Sustain. Energy Rev. 14 (2010) 430–437, https://doi.org/10.1016/j.rser.2009.07.028.

[8] P. Breslow, D. Sailor, Vulnerability of wind power resources to climate change in the continental United States, Renew. Energy 27 (2002) 585–598, https://doi.org/10.1016/S0960-1481(01)00110-0.

[9] D.J. Sailor, M. Smith, M. Hart, Climate change implications for wind power resources in the Northwest United States, Renew. Energy 33 (2008) 2393–2406, https://doi.org/10.1016/j.renene.2008.01.007.

[10] S.E. Haupt, J. Copeland, W.Y.Y. Cheng, Y. Zhang, C. Ammann, P. Sullivan, A method to assess the wind and solar resource and to quantify interannual variability over the United States under current and projected future climate, J. Appl. Meteorol. Climatol. 55 (2016) 345–363, https://doi.org/10.1175/JAMC-D-15-0011.1.

[11] D.L. Johnson, R.J. Erhardt, Projected impacts of climate change on wind energy density in the United States, Renew. Energy 85 (2016) 66–73, https://doi.org/10.1016/j.renene.2015.06.005.

[12] G. Roshan, M.S. Najafei, Á.M. Costa, J.A. Orosa, Effects of climate change on wind energy production in Iran, Arab. J. Geosci. 8 (2015) 2359–2370, https://doi.org/10.1007/s12517-014-1374-2.

[13] E.B. Pereira, F.R. Martins, M.P. Pes, E.I. da Cruz Segundo, A. de A. Lyra, The impacts of global climate changes on the wind power density in Brazil, Renew. Energy 49 (2013) 107–110, https://doi.org/10.1016/j.renene.2012.01.053.

[14] A.F. Pereira de Lucena, A.S. Szklo, R. Schaeffer, R.M. Dutra, The vulnerability of wind power to climate change in Brazil, Renew. Energy 35 (2010) 904–912, https://doi.org/10.1016/j.renene.2009.10.022.

[15] S. Kulkarni, M.C. Deo, S. Ghosh, Changes in the design and operational wind due to climate change at the Indian offshore sites, Mar. Struct. 37 (2014) 33–53, https://doi.org/10.1016/j.marstruc.2014.02.005.

[16] C. Fant, C. Adam Schlosser, K. Strzepek, The impact of climate change on wind and solar resources in southern Africa, Appl. Energy 161 (2016) 556–564, https://doi.org/10.1016/j.apenergy.2015.03.042.

[17] 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, Clim. Change 128 (2015) 99–112, https://doi.org/10.1007/s10584-014-1291-0.

[18] E. Kjellström, G. Nikulin, U. Hansson, G. Strandberg, A. Ullerstig, 21st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations, Tellus Ser. A Dyn. Meteorol. Oceanogr. 63 (2011) 24–40, https://doi.org/10.1111/j.1600-0870.2010.00475.x.

[19] M. Gaetani, E. Vignati, F. Monforti, T. Huld, A. Dosio, F. Raes, Climate modelling and renewable energy resource assessment, JRC Sci. Policy Rep. (2015), 2015/04/20 JRC Publication.

[20] A. Devis, N.P.M. Van Lipzig, M. Demuzere, Should future wind speed changes be taken into account in wind farm development? Environ. Res. Lett. 13 (2018) https://doi.org/10.1088/1748-9326/aabff7.

[21] J.S. Hosking, D. Macleod, T. Phillips, C.R. Holmes, P. Watson, E.F. Shuckburgh, D. Mitchell, Changes in European wind energy generation potential within a 1.5 °c warmer world, Environ. Res. Lett. 13 (2018), https://doi.org/10.1088/1748-9326/aabf78.

[22] I. Tobin, S. Jerez, R. Vautard, F. Thais, E. Van Meijgaard, A. Prein, M. Déqué, S. Kotlarski, C.F. Maule, G. Nikulin, T. Noël, C. Teichmann, Climate change impacts on the power generation potential of a European mid-century wind farms scenario, Environ. Res. Lett. 11 (2016) 34013, https://doi.org/10.1088/1748-9326/11/3/034013.

[23] I. Tobin, W. Greuell, S. Jerez, F. Ludwig, R. Vautard, M.T.H. van Vliet, F.-M. Bréon, Vulnerabilities and resilience of European power generation to 1.5 °C, 2 °C and 3 °C warming, Environ. Res. Lett. 13 (2018), 044024, https://doi.org/10.1088/1748-9326/aab211.

[24] N. RM Kirchner Bossi, R. García Herrera, L. Prieto, Trigo, A long-term perspective of wind power output variability, Int. J. Climatol. 35 (35) (2015) 2635–2646, https://doi.org/10.1002/joc.4161.

[25] G. Gómez, W.D. Cabos, G. Liguori, D. Sein, S. Lozano-Galeana, J. Fita, L. Fernandez, M.E. Magariño, P. Jimenez-Guerrero, J.P. Montávez, M. Domínguez, R. Romera, M.A. Gaertner, Characterization of the wind speed variability and future change in the Iberian Peninsula and the Balearic Islands, Wind Energy 19 (2016) 1223–1237, https://doi.org/10.1002/we.

[26] J.A. Santos, C. Rochinha, M.L.R. Liberato, M. Reyers, J.G. Pinto, Projected changes in wind energy potentials over Iberia, Renew. Energy 75 (2015) 68–80, https://doi.org/10.1016/j.renene.2014.09.026.

[27] P.M.M. Soares, D.C.A. Lima, R.M. Cardoso, M.L. Nascimento, A. Semedo, Western Iberian offshore wind resources: more or less in a global warming climate? Appl. Energy 203 (2017) 72–90, https://doi.org/10.1016/j.apenergy.2017.06.004.

[28] D. Hdidouan, I. Staffell, The impact of climate change on the levelised cost of wind energy, Renew. Energy 101 (2017) 575–592, https://doi.org/10.1016/j.renene.2016.09.003.

[29] L. Cradden, D. Burnett, A. Agarwal, G. Harrison, Climate change impacts on renewable electricity generation, Infrastruct. Asset Manag. 2 (2015) 131–142, https://doi.org/10.1680/iasma.14.00034.

[30] J. Cronin, G. Anandarajah, O. Dessens, Climate change impacts on the energy system: a review of trends and gaps, Clim. Change 151 (2018) 79–93.

[31] K. Solaun, E. Cerdá, The impact of climate change on the generation of hydroelectric power-a case study in southern Spain, Energies 10 (2017), https://doi.org/10.3390/en10091343.

[32] E. Sharp, P. Dodds, M. Barrett, C. Spataru, Evaluating the accuracy of CFSR reanalysis hourly wind speed forecasts for the UK, using in situ measurements and geographical information, Renew. Energy 77 (2015) 527–538, https://doi.org/10.1016/j.renene.2014.12.025.

[33] D. Jacob, J. Petersen, B. Eggert, A. Alias, O.B. Christensen, L.M. Bouwer, A. Braun, A. Colette, M. Déqué, G. Georgievski, E. Georgopoulou, A. Gobiet, L. Menut, G. Nikulin, A. Haensler, N. Hempelmann, C. Jones, K. Keuler, S. Kovats, N. Kröner, S. Kotlarski, A. Kriegsmann, E. Martin, E. van Meijgaard, C. Moseley, S. Pfeifer, S. Preuschmann, C. Radermacher, K. Radtke, D. Rechid, M. Rounsevell, P. Samuelsson, S. Somot, J.F. Soussana, C. Teichmann, R. Valentini, R. Vautard, B. Weber, P. Yiou, EURO-CORDEX: new high-resolution climate change projections for European impact research, Reg. Environ. Change 14 (2014) 563–578, https://doi.org/10.1007/s10113-013-0499-2.

[34] D.P. van Vuuren, J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, S.K. Rose, The representative concentration pathways: an overview, Clim. Change 109 (2011) 5–31, https://doi.org/10.1007/s10584-011-0148-z.

[35] T.F. Stocker, D. Qin, G.-K. Plattner, M.M.B. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley, Climate Change 2013 - The Physical Science Basis, 2013, https://doi.org/10.1038/446727a.

[36] S. Trzaska, E. Schnarr, A review of downscaling methods for climate change projections, United States Agency Int. Dev. by Tetra Tech ARD, 2014, pp. 1–42.

[37] D. Jager de, C. Klessmann, E. Stricker, T. Winkel, E. Visser de, M. Koper, M. Ragwitz, A. Held, G. Resch, S. Busch, C. Panzer, A. Gazzo, T. Roulleau, P. Gousseland, M. Henriet, A. Bouillé, Financing Renewable Energy in the European Energy Market Financing Renewable Energy in the European Energy Market, European Commission, Brussels, Belgium, 2011, https://doi.org/10.13140/2.1.3115.2645.

[38] IRENA, Renewable Energy Technologies: Cost Analysis Series. Wind Power, International Renewable Energy Agency, United Arab Emirates, Abu Dhabi, 2012.

[39] M.I. Blanco, The economics of wind energy, Renew. Sustain. Energy Rev. 13 (2009) 1372–1382, https://doi.org/10.1016/j.rser.2008.09.004.

[40] IDAE, Análisis de estándares de proyectos de producción de electricidad en régimen especial, Instituto para la Diversificación y Ahorro de la Energía, Madrid, Spain, 2014.

[41] S. C Krohn, S. Auwerbuch, P.E. Morthorst, M. Blanco, F. Van Hulle, Kjaer, The

Economics of Wind Energy, European Wind Energy Association, 2009.
[42] P.E. I Morthorst, H. Auer, A. Garrad, Blanco, The Economics of Wind Power, 2009. https://www.wind-energy-the-facts.org/index-4.html.
[43] IDAE, Evolución tecnológica y prospectiva de costes por tecnologías de energías renovables. Estudio Técnico PER 2011-2020, Instituto para la Diversificación y Ahorro de la Energía, Madrid, Spain, 2011.
[44] R. Davy, N. Gnatiuk, L. Pettersson, L. Bobylev, Climate change impacts on wind energy potential in the European domain with a focus on the Black Sea, Renew. Sustain. Energy Rev. 81 (2018) 1652–1659, https://doi.org/10.1016/j.rser.2017.05.253.
[45] D. Jacob, H. Hueging, J.G. Pinto, K. Born, R. Haas, Regional changes in wind energy potential over Europe using regional climate model ensemble projections, J. Appl. Meteorol. Climatol. 52 (2012) 903–917, https://doi.org/10.1175/jamc-d-12-086.1.
[46] D. Carvalho, A. Rocha, M. Gómez-Gesteira, C. Silva Santos, Comparison of reanalyzed, analyzed, satellite-retrieved and NWP modelled winds with buoy data along the Iberian Peninsula coast, Remote Sens. Environ. 152 (2014) 480–492, https://doi.org/10.1016/j.rse.2014.07.017.
[47] P. Mir-Artigues, E. Cerdá, P. Del Río, Analyzing the impact of cost-containment mechanisms on the profitability of solar PV plants in Spain, Renew. Sustain. Energy Rev. (2015), https://doi.org/10.1016/j.rser.2015.02.005.
[48] Red Eléctrica de España, Las energías renovables en el sistema eléctrico español 2016, Red Eléctrica de España, 2017.