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RESEARCH ARTICLE

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Climate change impacts on wind energy generation in Ireland

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Abstract

An ensemble of high-resolution regional climate model simulation data is used to examine the impacts of climate change on offshore and onshore wind energy generation in Ireland. Two Representative Concentration Pathway (RCP) scenarios (RCP 4.5 and 8.5) are analysed for the mid-term (2041–2060) and the long-term (2081–2100) future. Wind energy is projected to decrease (≤2%) overall in future climate scenarios. Changes are evident by mid-century and are more pronounced by late 21st century, particularly for RCP 8.5 offshore. Seasonally, wind energy is projected to decrease by less than 6% in summer and to increase slightly in winter (up to 1.1%). The distinct changes in different parts of the power curve, presented here for the first time, show a reversed pattern of duration at certain levels of the power curve. In summer, there is an increase of low-power and a decrease of high-power generation, whereas during winter, there is a projected increase in the time spent at high power. This could lead to diverse consequences for system operators depending on the season. The impacts of climate change on the duration and frequency of long periods (longer than 24 h) of low-/high-power wind energy events in Ireland are also presented. The frequency of low-power events is projected to increase slightly, especially during summer. Onshore and offshore events are considered separately, demonstrating the complementarity of developing both onshore and offshore wind farms for future energy systems. Regional analysis highlights the benefit of developing a geographically dispersed wind farm network incorporating different local wind conditions.

KEYWORDS
climate change, high-power events, Ireland, low-power events, wind energy

1 | INTRODUCTION

In 2018, 32.5% of all electricity in Ireland was generated from renewable sources, the majority of which (27.6%) was attributed to wind energy.[1] Global wind capacity has increased in recent years to 651 GW (2019) which is enough to provide an estimated 27.3% of global electricity generation by the end of 2019.[2] Transitioning to energy supply that depends heavily on wind power in a changing climate requires an understanding of how future projections of the relevant weather variables translate to wind energy generation. With an increasing global dependency on renewable resources, it is important to understand the impacts of weather on the energy system and how this is projected to change in the future.

Renewable energy is set to play an increasingly important role in reducing emissions, however with their dependency on weather, they are intermittent by nature. This poses a problem in maintaining a reliable and stable energy supply into the future.

Multi-model ensembles are a valuable approach to study climate change as they give a probabilistic view of climate projections. There are multiple sources of uncertainty associated with future climate projections, and an ensemble of regional climate models (RCMs) driven by global climate models (GCMs) can address part of this uncertainty. The Intergovernmental Panel on Climate Change (IPCC) outlines a range of possible Representative Concentration Pathway (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5) scenarios, to account for uncertainties in future projections of the atmospheric composition, which affects the radiation balance of Earth, thereby taking further uncertainties into account.[3–5]

Climate projections indicate a relatively uniform southward shift in wind power potential with global warming, with decreases in the Northern Hemisphere mid-latitudes.[6] Climate projections generally illustrate a decrease in wind speed throughout most of Europe,[6–8] although there are local variations and results depend on the ensemble of climate models studied. There is uncertainty in the consequences for storms over Ireland with some studies suggesting an increase in storm intensity[9–12] while for the changes in the number of storms, results show either increases,[10,11] no clear trend as they depend on the model used[9] or a decrease.[12] Therefore, the impacts of climate change can have varying effects on the potential future wind power generation. Cyclone tracks of extreme storms are projected to extend further south over Ireland by the mid-century (2041–2060).[7]

Around Ireland and the United Kingdom, wind power potential is projected to decrease by approximately 0%–10% by the end of the century under RCP 4.5 and 8.5 scenarios. These reductions are seasonally dependent with larger changes in summer than in winter.[6,13] Inter-annual variability, whether natural variability due to internal climate modes or due to the impacts of anthropogenic climate change, poses a risk to the wind energy industry and associated future projects in which wind farm resources and operations may change. In addition, there are little or no significant changes in the intra-annual and inter-annual variability of future wind energy in the UK–Ireland region.[13,14] On the contrary, Reyers et al[15] predict that wind energy output over the United Kingdom and Ireland will have no statistically significant changes on average in the long term under the RCP 8.5 scenario, but that there will be stronger intra-annual variability of future wind energy output. There is a seasonality to the impacts of climate change for Irish wind energy generation, with an increase during winter months of approximately 4%–10% and a decrease of approximately 4%–14% during summer months in the mid-term (2021–2060).[16,17] However, the climate change signal is of similar magnitude to climate variability. Offshore wind energy is developing, with more potential to harness larger amounts of wind power than most onshore wind farms. There is little change expected in the region around Ireland in offshore wind power generation for the 21st century.[18]

Along with the general changes in power generation, long periods of low-power generation have an impact on the smooth running of the power system, as back-up energy supplies may be needed to meet demand. Historical low-wind power events in Germany are found to occur most in summer.[19] The spatial pattern of wind energy generation during the most extreme low-wind power event differs from the average distribution of capacity factor throughout the country. This suggests that low-wind events can be very pronounced in regions with good average wind resources. In Ireland, even a single event with a return period of 10 years in an area with a favourable wind regime can reduce the annual energy yield of a wind farm by 5%.[20] The temporal and spatial heterogeneity of renewable resources essentially determines the balance of energy systems and more homogeneous wind conditions over Europe result in simultaneous power generation shortages.[21] An increase in wind speed correlations between all locations in a country imply more homogeneous wind conditions, suggesting that more backup energy will be required during future low-wind power events. To ensure resilience in supply, Leahy and McKeogh[22] show that there are advantages to increasing the installed capacity in areas even with existing high levels of installed capacity. In order to reduce wind power variability and the likelihood of wind droughts, introducing more installed capacity to lower installed capacity regions can reduce ramps and low wind power production.

Weber et al[23] suggest that only changes in the temporal aspects such as the duration of low-wind periods or the seasonal wind variability can lead to changes in backup energy and storage needs. There is an increased likelihood for long periods of low-wind generation (defined as the time series when wind power generation is continuously below average) and also an increase in the seasonal wind variability under RCP 8.5 by the end of the century (2070–2100). Low-wind power events are also projected to increase in duration by the end of the century. The winter-summer ratio is projected to increase for most of Central and North-Western Europe leading to the high probability of long periods of low-wind power generation. Wind energy system operators require knowledge of the inter-annual variability of wind energy generation throughout the lifetime of wind farms. The impacts of inter-annual variability can determine the risk associated with a potential wind farm project.[24,25] However, caution must be taken when assessing the inter-annual variability for future wind projects as it can be overestimated compared to observations.[26]

This study outlines how the effects of a changing climate on wind energy generation can be quantified at high-resolution, in the mid-term (2041–2060) and long-term (2081–2100) future. This is demonstrated by making use of high-resolution RCM simulation data for Ireland. The expected growth in installed capacity and advancements in turbine technology are foreseen to have a greater impact on wind energy generation than climate change impacts. However, this study aims to understand the isolated effects of weather and climate on future energy systems without introducing other dimensions of uncertainty. Section 2 presents the climate models used in this study which are used as input data for the wind energy capacity model described in Section 3. The focus here is on future projections of onshore and offshore wind energy in Ireland and the overall wind energy results are presented in Section 4. In Section 5, the ensemble of high-resolution RCMs is used to study the frequency and duration of long periods of consistently high- or low-power wind energy conditions which haven't been examined in Ireland before. Finally, conclusions are discussed in Section 6.

2 | DATA

2.1 | RCM simulations

RCM simulation data were obtained from the Irish Centre for High End Computing (ICHEC) and EURO-CORDEX.[27] For a description of the ICHEC RCM experiments please refer to Nolan and Flanagan.[28] Two RCMs, the Consortium for Small-scale Modelling–Climate Limited-area Modelling (COSMO-CLM) and the Rossby Centre regional atmospheric model (RCA4), are used to downscale five GCM datasets, see Table 1 for details. Missing data are described in Appendix A. These model simulation data are obtained for the island of Ireland and the surrounding sea, at 3-hourly temporal resolution. Wind speed at 10 m (near surface in EURO-CORDEX) (W_{10m}) for historical (1981–2000) and two future periods (2041–2060 and 2081–2100) under two climate scenarios (RCP 4.5 and RCP 8.5), are extrapolated to turbine hub-height using the wind profile power law:

$$W_{hub} = W_{10m}\left(\frac{125}{10}\right)^{\alpha} \quad (1)$$

where W_{hub} is the wind speed at turbine hub-height of 125 m and α is the wind shear exponent and is commonly set to 1/7 for neutral stability conditions. Although equation 1 does not account for temporal and spatial variations in surface roughness and atmospheric stability conditions, which can affect the wind speed profile, it is widely used in wind energy analysis.[6,29] The extrapolated hub-height wind speeds, W_{hub}, are used as input to the wind energy model, described in Section 3.

2.2 | Historic reanalysis data

The Met Éireann Re-Analysis (MÉRA) dataset[30] produced by the Irish meteorological service is used as a representation of the 'observed' historical climate, wind capacity model bias correction, and for RCM data validation. MÉRA is the highest-resolution regional reanalysis dataset available for Ireland and provides a good representation of recent Irish climate.[31] Further analysis of the skill of MÉRA relative to observations in Ireland is examined in Gleeson et al[30] and Whelan et al.[32] MÉRA data, W_{hub}, at hourly resolution and 2.5-km grid-spacing for the historic period, 1981–2000, are used. MÉRA winds are available at heights of 10 and 125 m, so no extrapolation is needed.

3 | WIND ENERGY CAPACITY MODEL

The wind energy capacity model involves converting wind speeds at hub-height to power output using manufacturers' power curves for single turbines.[33] Vestas-V110-2000 is chosen as a representative turbine. The wind energy model requires wind speed at hub-height (W_{hub}) as an input,

TABLE 1 The climate model data used in this study

	RCM	GCM	Horizontal grid spacing (km)
ICHEC	CCLM	CNRM-CM5	4
ICHEC	CCLM	EC-EARTH	4
ICHEC	CCLM	HadGEM2-ES	4
ICHEC	CCLM	MPI-ESM-LR	4
ICHEC	CCLM	MIROC5	4
EURO-CORDEX	RCA4	CNRM-CM5	~12.5
EURO-CORDEX	RCA4	EC-EARTH	~12.5
EURO-CORDEX	RCA4	HadGEM2-ES	~12.5
EURO-CORDEX	RCA4	MPI-ESM-LR	~12.5
EURO-CORDEX	RCA4	CM5A-MR	~12.5
EURO-CORDEX	RCA4	NorESM1-M	~12.5

Note: The regional climate model (RCM): COSMO-CLM (CCLM) and RCA4, the corresponding downscaled global climate model (GCM), and the horizontal grid spacing.

which is then fed through the power curve to estimate capacity factors. To reduce any bias in the data and bring the capacity factors in line over the historical period, a bias correction has been applied to the turbine power curves before the climate model W_{hub} data are applied to them.

This bias correction is calculated by selecting the cut-in speed (S_{cut-in}), the rated capacity speed (S_{rated}), and the cut-out speed ($S_{cut-out}$), from the power curve. The percentile for these wind speeds is calculated for the MÉRA data (approximately 3%, 70% and 98%, respectively). The bias-adjusted S_{cut-in}, S_{rated} and $S_{cut-out}$ are then calculated by finding the wind speed in the climate model data where the relevant percentile occurs. Cubic splines are fitted to the original power curve and then applied to the bias-adjusted S_{cut-in}, S_{rated} and $S_{cut-out}$ values to produce the bias-adjusted power curves. This is done separately for each onshore and offshore location and for each dataset. An example of the bias-adjusted turbine power curves is shown in Figure 1, where the overestimation in offshore data compared to MÉRA is evident, along with the underestimation onshore.

3.1 | Island of Ireland notional aggregate wind power

There is an all-island single electricity market in place for the island of Ireland. An island of Ireland notional aggregate onshore wind power is calculated from a representative subset of Irish Wind Energy Association (IWEA) connected wind farms active as of the end of 2018. Eighteen of the largest wind farms, at geographically dispersed locations, are selected (Figure 2). Each wind farm is assigned the same installed capacity. Wind farm outputs are calculated from the nearest model grid-point and are summed together to calculate a notional island of Ireland projected aggregate wind energy generation.

Offshore wind farm locations are selected from wind farm locations which have either approved or planned status. For comparison purposes, wind farms at geographically dispersed locations were selected; two off the west coast of Ireland and two in the Irish Sea. A 7×7 grid-point region (3×3 grid-points for the lower spatial resolution of EURO-CORDEX data) around each offshore wind farm location is selected and each grid-point is assigned equal proportion of the installed capacity. Each region is used to represent the wind power at that wind farm location and the total national offshore wind power is calculated from the sum of all grid-points in the four offshore regions, see Figure 2.

There are some parameters in this study which the results are sensitive to. These include the choice of turbine type, that is, the shape of the power curve. A brief analysis of this sensitivity was performed here using different turbines for onshore and offshore wind farms and the main results and conclusions remain consistent. Moemken et al[8] also performed a sensitivity test on the choice of turbine and concluded the choice had a negligible impact on the projected future changes.

4 | OVERALL WIND ENERGY RESULTS

In the historic period (1981–2000), MÉRA has an average wind capacity factor of 64% onshore and 66% offshore, with winter producing up to 25% more wind energy than summer. In general, wind energy is estimated to decrease slightly in future climate scenarios (Figure 3). Overall reductions range from −0.4% to −1.2% onshore and −0.5% to −2% offshore. However, there is uncertainty among the different climate models. Changes are described as robust changes when more than 66% of the ensemble member models (corresponding to seven out of 11 members) agree in the direction of change following the IPCC definition.[5,27] Results for the overall changes in wind energy are robust in all climate scenarios.

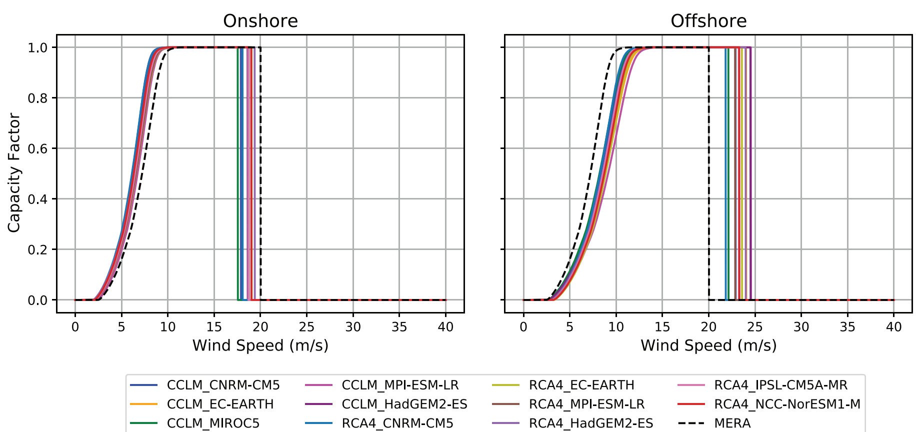

FIGURE 1 The original manufactures turbine power curve (black dashed) for (A) onshore and (B) offshore, along with the bias-adjusted (method described in Section 3) power curves for each climate model dataset [Colour figure can be viewed at wileyonlinelibrary.com]

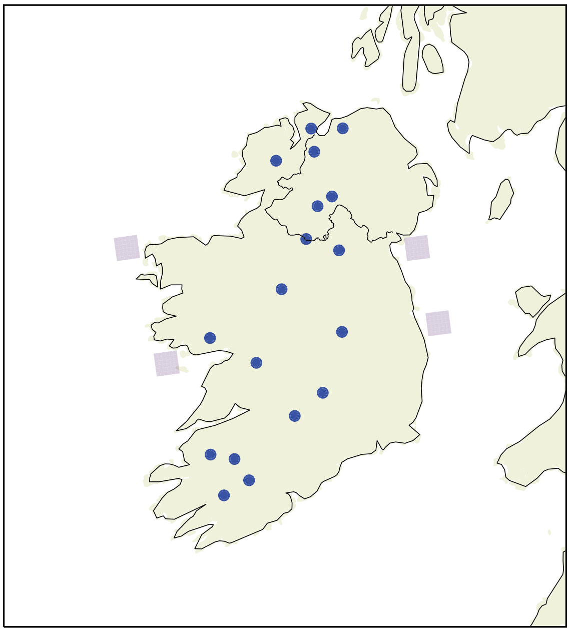

FIGURE 2 The notional island of Ireland wind power set-up is represented by 18 onshore wind farm locations (blue circles) and four offshore regions (grey boxes). Offshore regions consist of 7 × 7 grid-points for CCLM RCMs and 3 × 3 grid-points for the larger grid spacing of RCA4 RCMs [Colour figure can be viewed at wileyonlinelibrary.com]

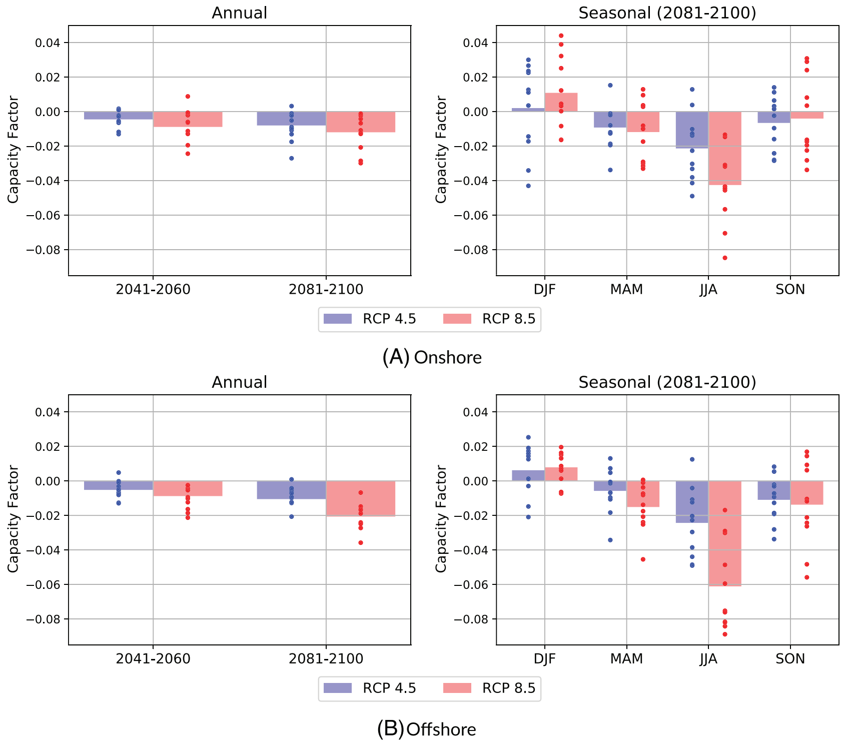

FIGURE 3 The future changes in (A) onshore and (B) offshore wind energy compared to the historic baseline period (1981–2000) for (left) the full year and (right) seasonally (DJF: winter, MAM: spring, JJA: summer, SON: autumn) during the late-century, 2081–2100, for RCP 4.5 (blue) and RCP 8.5 (red). The bars are the multi-model ensemble mean and the dots represent individual climate models [Colour figure can be viewed at wileyonlinelibrary.com]

Wind energy is predicted to decrease in summer with larger decreases projected for offshore than onshore. Changes are evident by mid-century, and are more pronounced by the end of the century. On the other hand, by the end of the century, wind energy during winter is projected to increase slightly. Wind energy changes are robust for most seasons (except for SON onshore) at the end of the century.

An overlap score is used to measure the similarity between two distributions. It is defined as

$$O_{score} = 100 \times \sum_{1}^{n} min(Z_A, Z_B), \tag{2}$$

where n is the number of bins used to calculate the probability distribution function and Z_A and Z_B are the frequency of values in a given bin from data A and B. 100% indicates perfect agreement (e.g., A and B agree) and 0% indicates no agreement (e.g., A and B have no values in common). An O_{score} of 93.89% onshore and 97.37% offshore between MÉRA and the multi-model ensemble (MME) shows there is good agreement historically between the climate models and the reanalysis data. Past and future climate data can also be compared with the O_{score} to determine the magnitude of climate change. The O_{score} results, presented in Table 2, highlight the small magnitude of impact that climate change is projected to have on overall wind energy in future scenarios. These results suggest that there will be a larger impact from climate change on offshore wind farms, particularly by the end of the century for RCP 8.5. Seasonally, there is a larger O_{score} during winter compared to summer suggesting climate change will have a larger impact on summer wind energy generation, supporting the results of Figure 3.

The impact of climate change on the overall wind energy production can be highly sensitive to where along the turbine rating curve the change occurs. This is an important consideration for system operators, as a decrease in the lower portion of the distribution may require alternative sources of energy to meet demand whereas an increase in the upper portion of the distribution leads to increased filling of storage reserves and potential curtailment. Figure 4 shows changes in the amount of time spent at different levels of power generation, from less than 10% rated on the turbine power curve, to more than 90% rated on the turbine power curve. It highlights the uncertainty among the climate models, although this ensemble is robust at almost all sections of the distribution (except the 10%–30% section in DJF and the 50%–70% section in JJA). There is a reversed pattern in the change of the distribution of wind energy in winter and summer, which supports the overall seasonal changes of a decrease in wind energy during summer compared to an increase in winter. This draws attention to the potential need for additional back-up energy supply during summer in future climate scenarios. Similar results are seen for offshore wind energy.

TABLE 2 The O_{score} results (%) for multi-model ensemble (MME) changes in wind energy from the historic reference period, 1981–2000

	RCP 4.5		RCP 8.5	
	Onshore	Offshore	Onshore	Offshore
2041–2060	99.17	99.02	98.84	98.23
2081–2100	98.73	98.50	98.37	96.64

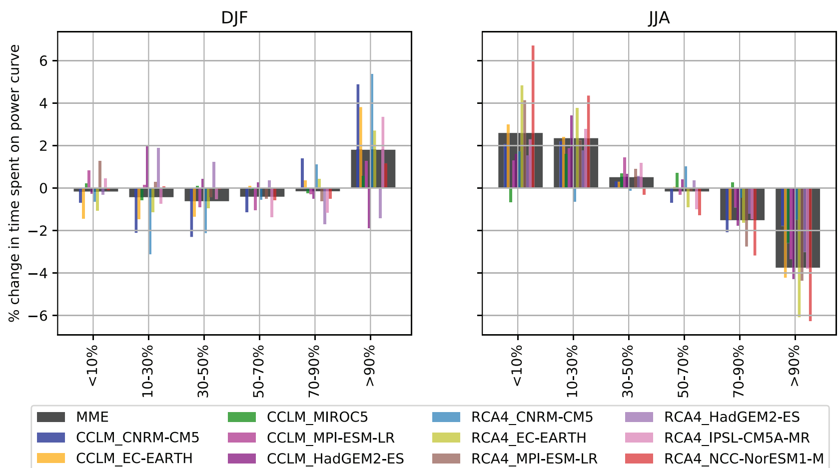

FIGURE 4 The changes (%) in time spent on sections of the power curve for onshore wind power distribution at the end of the century (2081–2100) under RCP 8.5 compared to the historic baseline period (1981-2000) for winter (DJF) and summer (JJA). The grey bars are the multi-model ensemble (MME) mean and the coloured bars represent climate models, in each section of the turbine power curve: [0, 10), [10, 30), [30, 50), [50, 70), [70, 90) and [90, 100] [Colour figure can be viewed at wileyonlinelibrary.com]

5 | DURATION OF EXTREME EVENTS

In this section, continuous low- or high-power events are defined as consecutive periods of time in which the capacity factor remains below/above a certain threshold. Here the focus is on events longer than 1 day, as these are important to the wind energy industry when considering storage requirements. In the historic period, low-power events are less common than high-power events in both onshore and offshore wind energy (Figure 5). Low-power events generally have a slightly longer duration onshore than offshore, except at the 20% threshold. Low-power events occur more frequently offshore than onshore at the 5% and 10% thresholds. High-power events are more similar for onshore and offshore locations, with slightly more time spent during onshore high-power events in total.

5.1 | Climate projections for low-power events

In this section, we define low-power events as consecutive hours with capacity factor consistently below a threshold of 10% (including 0% power generation). Short events of up to about 2 days in length are relatively frequent, while long events are much rarer. Figure 6 shows the spread among the ensemble of climate models for onshore low-power events. The median of the ensemble results suggests that low-power events will persist for less than three days and also remain relatively constant throughout the climate periods. However, when the climate models are examined separately a better representation of potential extreme durations is given, which may be several days longer, as seen in Figure 6. The 95th percentile of onshore event duration also remains constant, at 63–66 hours, throughout the climate periods. The most extreme 5% of events, however, do change for future climate scenarios. Figure 6 suggests that the single longest event may increase to more than 8 days by the end of the century. It also highlights how much of an outlier the single longest event is, as there is a noticeable gap between the longest event and the next longest event. For example, for RCP 4.5, there is more than a 3-day difference between the longest and second longest event at the end of the century. Results show that RCA4 RCM ensemble members generally have longer periods of consecutive low power. The four longest low-power events in each climate period belong to RCA4 RCM ensemble members while the top three shortest low-power events consistently belong to the CCLM RCM group.

An event is assigned to the season in which at least 50% of the event occurs. Long duration low-power events are most frequent in summer (35%) followed by autumn (29%), which is consistent throughout all climate scenarios. This suggests that substantial extreme events can occur throughout the year, and not just during summer months. In Ireland, weather-driven electricity demand is larger in winter due to space heating,

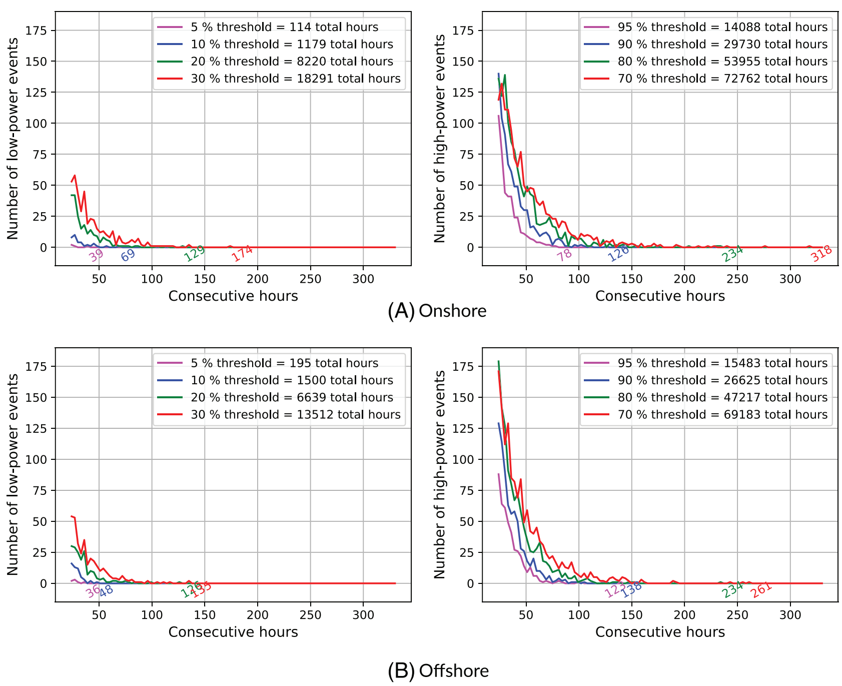

FIGURE 5 The number of (left) low-power events greater than 24 h with consecutive hours below the threshold capacity factor of 5%, 10%, 20% and 30%; and (right) high-power events above 70%, 80%, 90% and 95% capacity factor for (A) onshore and (B) offshore wind power for the historic baseline period (1981–2000) in MÉRA. The numbers indicate the individual longest consecutive number of hours at each threshold. The sum total number of hours in each situation is included in the legend [Colour figure can be viewed at wileyonlinelibrary.com]

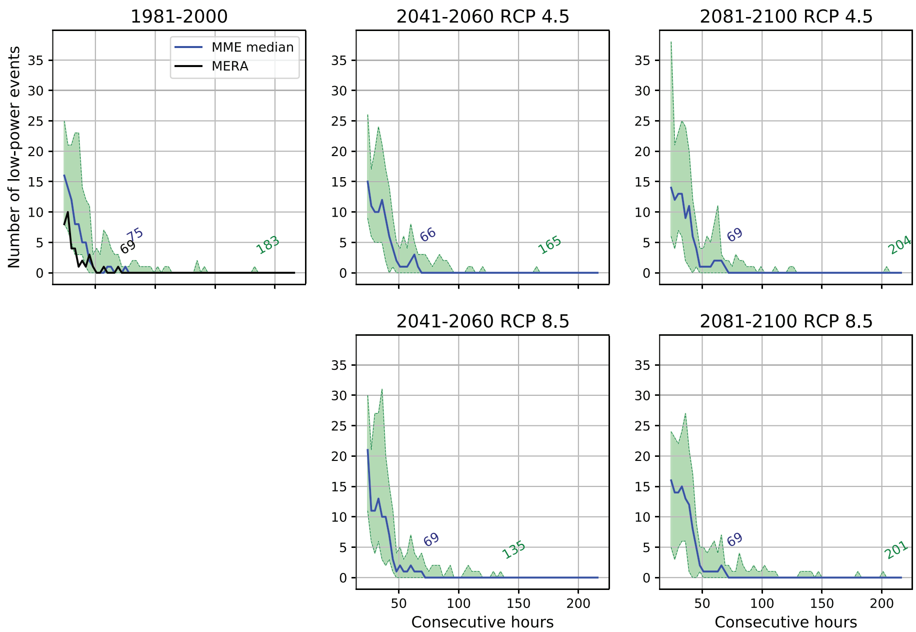

FIGURE 6 The number of onshore low-power events (<10% capacity factor) for each climate period and RCP scenario. The green shaded area represents the spread between the maximum and minimum of the multi-model ensemble (MME) of climate models. The blue line represents the median of the ensemble results at each point on the *x*-axis and in the historic period MÉRA (black line) is included for comparison purposes. The numbers represent the duration of the individual longest event for any model (green), the median (blue) and MÉRA (black) [Colour figure can be viewed at wileyonlinelibrary.com]

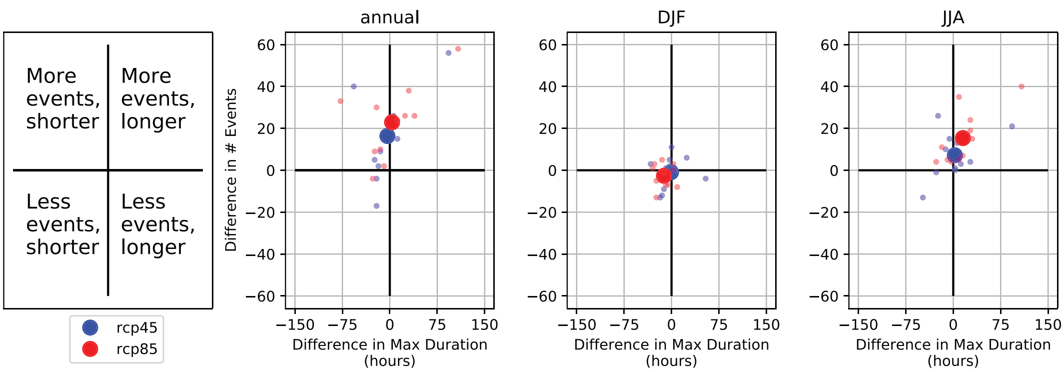

FIGURE 7 The changes in onshore low-power events (<10% capacity factor for at least 24 consecutive hours) in future scenarios for 2081–2100, RCP 4.5 (blue) and RCP 8.5 (red) relative to the historic period (1981–2000). The *y*-axes show the change in number of events and the *x*-axes show the change in maximum event duration (number of consecutive hours). The results are shown for the full year and for winter (DJF) and summer (JJA). The large dots represent the average results of multi-model ensemble while the small dots are the results for individual climate models [Colour figure can be viewed at wileyonlinelibrary.com]

whereas currently there is little air-conditioning in summer. Therefore, a low-power event in summer may not require the equivalent back-up energy as a winter event to sufficiently meet demand. The single longest event in the MME occurs during autumn in the historical period and changes to summer by the end of the century.

The impact of climate change on low-wind power onshore events is shown in Figure 7, where the average of the ensemble results shows an increase in the number of events in future scenarios compared to the historic period for the full year and for all seasons except winter. The increase in low-power events is largely due to the decrease in low wind speeds. Analysis of the low-power events finds that in the historic period there are no events due to wind speeds above cut-out speed. In 2041–2060 (both RCPs) and 2081–2100 (RCP 4.5) there are two climate models in each time period which have one low-power event each with wind speeds above cut-out speed, while in 2081–2100 (RCP 8.5) there is only one ensemble member with a single low-power event above cut-out speed. None of these events occur during summer. Therefore, this implies that the increase in low-power events is a result of the decrease in wind speed especially around the cut-in speeds. This supports the results of

Figure 4 in which there is an increase in the time spent at lower sections of the wind power distribution and a decrease in the wind speed at upper sections of the wind distribution in summer. Overall, by the end of the century the MME longest event is projected to remain relatively similar in duration, although when examined seasonally, the longest summer event is projected to increase slightly. There is a larger variability between the individual climate model members during summer than winter, as supported by the robustness of the ensemble for all but the changes in max duration during JJA in RCP 4.5. RCA4 RCM ensemble members have a larger contribution to the increase in JJA low-power events where the number of events is on average almost three times larger than for CCLM RCM ensemble members.

For offshore extreme low-wind power there are on average 76 low-power events lasting more than 24 h, of which the majority occur during summer (53%), with less than 6.2% of events occurring during winter. The single-longest extreme event occurs during autumn for the historic period (1981–2000) and 2041–2060 under RCP 4.5. However, there are numerous events during summer which are longer than the second longest event in autumn, particularly in the historic period. The single most extreme offshore event for each climate period occurs in the same season as those onshore. However, the single longest onshore event is not the same event as the longest offshore event, except in the historic period. This suggests that establishing a larger offshore fleet of wind farms in the future may compensate for long low-wind power onshore events and vice-versa.

The climate models project an increased frequency of low-power events offshore in future climate scenarios for all seasons. The majority of additional events occur during JJA, particularly under RCP 8.5 (Figure 8). There is more uncertainty regarding the change in the frequency of events during summer than in the other seasons, although the ensemble results are robust for all except DJF.

5.2 | Climate projections for high-power events

High-power or near-rated-power events are defined as the consecutive period in which each hour is above a threshold of 90% capacity factor. Overall, there is a projected decrease in the number of near-rated-power events in future scenarios compared to the historic period, consistent with the projected decrease in overall wind energy generation. However, there is a small increase in the number of high-power events during winter by the end of the century. The majority of onshore events (34.5% of events) occur during winter in all climate periods, whereas 30% of offshore events occur in both autumn and winter (Figure 9). There is less uncertainty in the impact of climate change on the frequency of events during summer. There is no consistency in which season the longest event will occur, although for both onshore and offshore it never occurs during summer. Under RCP 4.5 the individual longest onshore event is projected to decrease by 1 day (down to 150 h) while under RCP 8.5, an increase of 1 day is projected (up to 198 h) by the end of the century. Offshore events show an increase in duration of more than 2 days for RCP 8.5 while RCP 4.5 has a maximum change of 33 h.

5.3 | Regional analysis

Back-up energy and energy storage requirements in future wind energy systems are determined by the temporal and spatial heterogeneity of wind energy throughout the energy system network. Western offshore locations are windier than eastern offshore locations, due to the prevailing

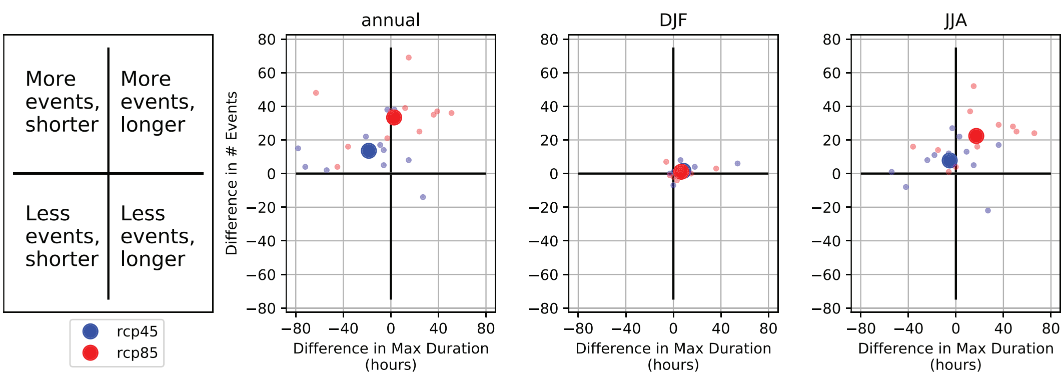

FIGURE 8 The changes in offshore low-power events (<10% capacity factor for at least 24 consecutive hours) in future scenarios for 2081–2100, RCP 4.5 (blue) and RCP 8.5 (red) relative to the historic period (1981–2000). The *y*-axes show the change in number of events and the *x*-axes show the change in maximum event duration (number of consecutive hours). The results are shown for the full year and for winter (DJF) and summer (JJA). The large dots represent the average results of multi-model ensemble while the small dots are the results for individual climate models [Colour figure can be viewed at wileyonlinelibrary.com]

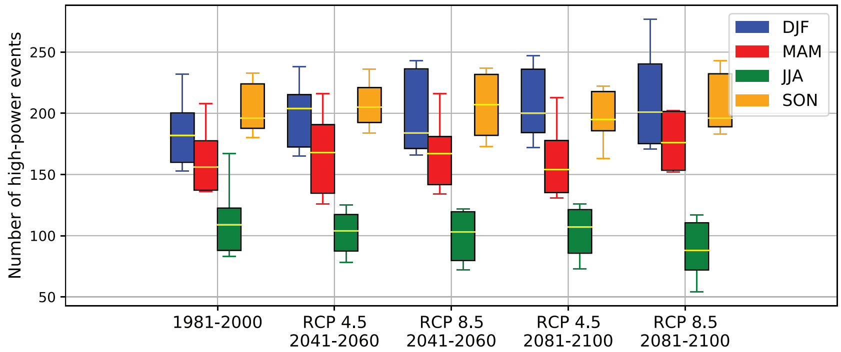

FIGURE 9 The number of offshore near-rated-power events (>90% capacity factor for at least 24 consecutive hours) in each climate period and RCP scenario, from the multi-model ensemble, seasonally (DJF: winter, MAM: spring, JJA: summer, SON: autumn). The box extends from the 25th to the 75th percentile values with the yellow line at the median and the whiskers extend from the 5th to the 95th percentile [Colour figure can be viewed at wileyonlinelibrary.com]

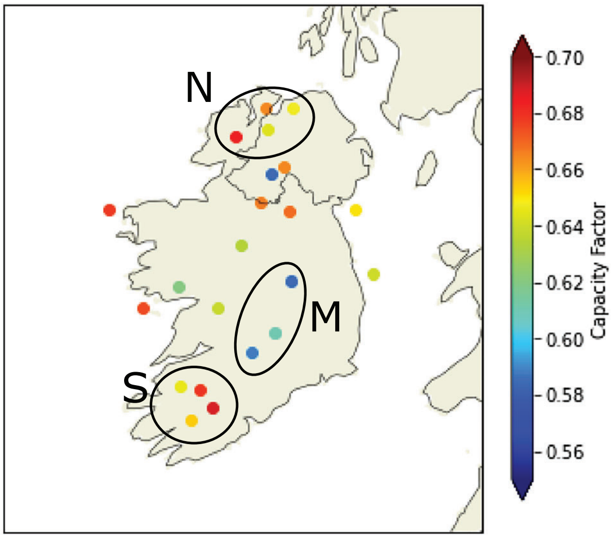

FIGURE 10 Average wind energy capacity factor for each wind farm calculated by MÉRA in the historic period (1981–2000). Onshore wind farms are grouped into regions, three regions are: north (N), midlands (M) and south (S) [Colour figure can be viewed at wileyonlinelibrary.com]

south-westerly wind in Ireland,[34] and therefore have a higher average capacity factor (of approximately +7%) throughout all seasons, as seen in Figure 10. This is also consistent with western offshore locations spending less time at low-power. There is a high correlation, approximately 0.79, between the two east-coast wind farms, and similarly for the two west-coast wind farms, 0.70. This correlation remains constant during the future mid-century and late-century. The average capacity factor difference between the east-coast and west-coast wind farms also remains relatively constant, at approximately 3.5% throughout all climate periods. This suggests that there is, in general, a uniform change in wind energy production for offshore wind farms.

West-coast offshore wind energy often has shorter low-power events than the east-coast, Figure 11. There is no consistency among the ensemble members as to which model produces the longest low-power event in either location. The longest event on the east-coast is not the same event as the longest event on the west coast, except in the historic period and at the end of the century under RCP 8.5. This suggests that geographically dispersed wind farms could help to alleviate the pressure on national power supply during low-wind scenarios. Similarly for onshore wind energy, consideration should be given to the spatial dispersion of wind farms. At the end of the century, low-power events are projected to get up to 12 h longer for midland wind farms which are already situated in a low-power region (region M in Figure 10), compared to the higher wind regime regions further north and south in the country (regions N and S in Figure 10), which have +8% larger average capacity factor compared to the midland region. A well-positioned, dispersed wind farm network which can take advantage of the different weather conditions may alleviate simultaneous wind power generation shortages.

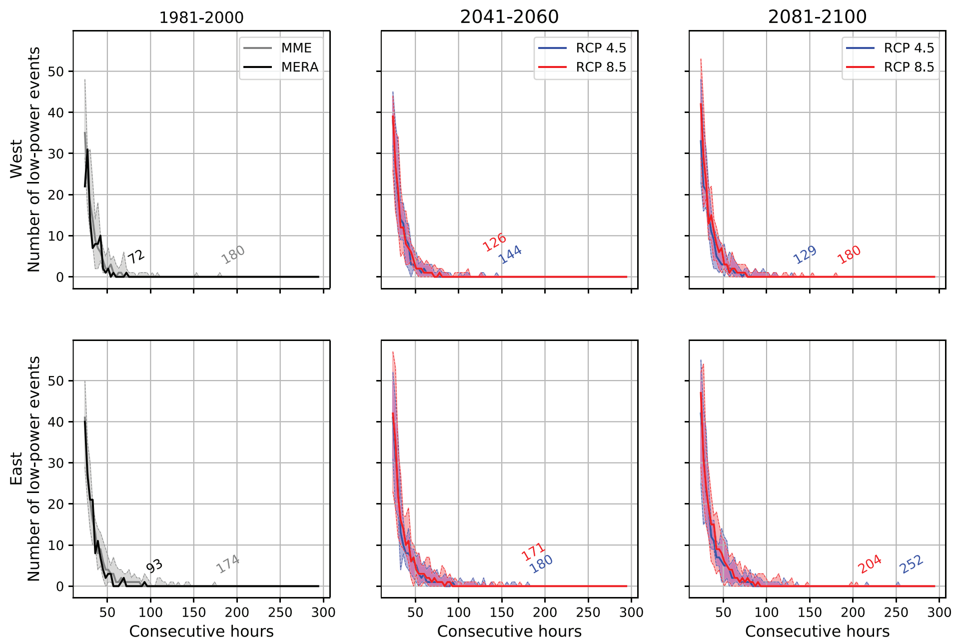

FIGURE 11 The number of offshore low-power events (<10% capacity factor) for each climate period and RCP scenario for (top) west-coast and (bottom) east-coast wind farms. The shaded area represents the spread between the maximum and minimum of the multi-model ensemble (MME) of climate models. The thick lines represent the median of the ensemble results at each point on the *x*-axis and in the historic period MÉRA (black line) is included for comparison purposes. The numbers represent the duration of the individual longest event [Colour figure can be viewed at wileyonlinelibrary.com]

6 | CONCLUSIONS

A multi-model ensemble of high-resolution climate models is used to address uncertainty in projections of future wind energy for Ireland. There is large variability between the climate models as all models do not project the same signal of change in future climate scenarios, although overall results are robust. This highlights the importance of using an ensemble of multiple climate models. In general, there is more consistency between the climate models during summer.

Overall, there is a projected decrease in wind energy (−0.4% to −2%), which supports the results of previous studies. There is a seasonality associated with the impacts due to climate change on wind energy resulting in a more pronounced decrease during summer, with projections predicted to decrease by less than 6%, compared to a slight increase during winter (up to 1.1%). Increases in winter and a more pronounced decrease in summer lead to larger intra-annual variability which could result in higher irregularity in wind energy production within a year. Distinct seasonal changes in different parts of the power curve are presented here for the first time, in particular, the reversed pattern in wind energy generation during summer and winter (Figure 4). This highlights the vulnerability of energy systems in winter when increased time at rated power may lead to curtailment and the increased time at low-power during summer which may lead to energy shortfall.

Along with the general changes in power generation, long periods of low- or high-power generation have an impact on the smooth running of the power system. This paper examines, for the first time, high- and low-power events for offshore wind farms along with the regional analysis of these events in Ireland. Low-power events are projected to increase in frequency (on average from +16 events onshore to +65 events offshore by the end of the century) together with slight increases in event duration (on average +9 h), particularly during summer. Results signify the essential planning of future wind farms in a diverse range of wind condition regimes to best capture the regional compatibility. The Irish offshore wind energy network is currently relatively small. However, results here suggest that developing the future offshore wind energy generation could allow the national energy system to maintain more consistent wind energy. Low-power offshore events are projected to have a more pronounced increase in duration during summer suggesting that a balance of onshore and offshore installed power will be needed to maintain energy system operations.

Extreme events are a necessary consideration for system operators as vulnerable energy systems may be exposed to energy shortfall and alternative sources of energy are required to meet demand, usually at a high cost, during low-power events. The projected decrease in wind speed is reflected by the increase in substantial low-power events and the decrease in rated-power events. These results are consistent with previous studies,[8,21] resulting in more back-up and storage required to stabilise the supply from wind-driven energy systems. This paper also presents novel results regarding the projected changes for low- and high-power events. It is primarily the longest 5% of events which are projected to experience a change in duration in future climates. Most notably this results in a slight increase in event duration during summer.

The overall results of a reduction in wind energy generation indicate that a continuously developing renewable energy system is necessary to maintain a stable and secure method of meeting society's demand for electricity. Studies like this are essential in order to influence the planning of future energy systems to operate in the most efficient manner.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interests.

DATA AVAILABILITY STATEMENT

MÉRA reanalysis data is available on request from the Irish Meteorological Service, Met Éireann. EURO-CORDEX data is available to download online (https://esgf-data.dkrz.de/search/cordex-dkrz/) (last accessed 6 May 2020). ICHEC climate model simulation data is available on request from ICHEC.

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APPENDIX A: MISSING CLIMATE MODEL DATA

There are missing hours/days at the end of the century in the GCM data which have passed down to the RCM data. These are substituted with the same time in the previous day if there is less than one day missing, if there is more than one day missing, the equivalent day and hour from the previous year is used to fill the missing times (see Table A1 for the list of missing data). As the climate period as a whole is being examined here, this should have minimal effects on the overall outcome.

TABLE A1 The dates for the missing RCM data which have been filled in to make complete records

	RCP 4.5	RCP 8.5
CCLM_HadGEM2-ES	2099-11-30 21:00 - 2100-12-30 21:00 (3121)	2099-12-30 09:00 - 2100-12-30 21:00 (2886)
CCLM_MIROC5	2100-12-31 09:00 - 2100-12-31 21:00 (5)	
CCLM_MPI_ESM_LR	2100-12-31 15:00 - 2100-12-31 21:00 (3)	2100-12-31 15:00 - 2100-12-31 21:00 (3)
RCA4_HadGEM2-ES	2099-12-01 00:00 - 2100-12-30 21:00 (3120)	2100-01-01 00:00 - 2100-12-30 21:00 (2880)

Note: The number in brackets are the total number of missing 3-hourly files.