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Persistence of low wind speed conditions and implications for wind power variability

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Abstract

As the penetration of wind generation increases on power systems throughout the world, the effects of wind variability on power systems are of increasing concern. This study focuses on sustained occurrences of low wind speeds over durations ranging from one hour to twenty days. Such events have major implications for the variability of energy yields from wind farms. This in turn influences the accuracy of wind resource assessment. The frequency analysis techniques commonly used to study wind variability cannot represent the autocorrelation properties of wind speeds and thus provide no information on the probabilities of occurrence of such sustained, low wind events. We present two complementary methods for assessing wind variability, runs analysis and intensity-duration frequency analysis, both with emphasis on characterising the occurrence of continuous, extended periods (up to several days) of low wind speeds. Multi-annual time series of hourly wind speeds from meteorological stations in Ireland are analysed with both techniques. Sustained 20-day periods corresponding to extremely low levels of wind generation are found to have return periods of around ten years in coastal areas. Persistent, widespread low wind speed conditions across the entire country are found to occur only rarely.

1. Introduction

The wind regime in Ireland is very favourable to wind energy generation, with mean unconstrained wind speeds greater than 6.5 m s^{-1} at 50 m above ground level over most of the country's land area, and even higher values in areas near the west coast [1]. There are two transmission system operators on the island of Ireland. The Northern Ireland and Republic of Ireland systems are interconnected and a single electricity market operates on the island. Over 1.7 GW of wind generation capacity is installed across the Republic of Ireland and Northern Ireland electricity systems [2, 3] The transmission system operator of the Republic is currently issuing connection offers for a further 3900 MW of wind capacity and there is 447 MW of capacity either under construction or consented in Northern Ireland [3, 4]. The government of the Republic of Ireland has set a target of 40% of electricity generation from renewable energy sources by 2020 [5] and it is envisaged that wind will make up by far the largest proportion of this target. One of the proposed 2020 generation portfolios suggests that 5800 MW of wind capacity will be required to meet this target [6]. Thus Ireland is set to become a test case for power system operations with high penetrations of wind generation.

Many previous studies have dealt with the short-term intermittency of renewable generators such as wind, e.g. [7, 8, 9]. Wind generators may produce no output power due to wind speeds falling below turbine cut-in thresholds or due to shutdowns in high wind speed conditions. Wind speeds below the cut-in threshold are far more prevalent than high wind shutdowns [10]. Quantifying the incidence of low wind speeds is therefore important, given the increasing penetration and geographical dispersal of wind energy generation on power systems such as the Irish one. A further issue of concern is the potential correlation of winter demand peaks and prolonged low wind power output, both often arising due to large, slow-moving high-pressure systems which typically bring low air temperatures and low wind speeds [11]. Therefore, this study is concerned with wind variability over multiple timescales from hours to days and the occurrence of relatively infrequent, but significant, prolonged periods of low wind speeds.

Integrating large amounts of wind generation to power systems will also require a shift in how existing, conventional thermal generators on the system are scheduled. Operational measures which can address the issue of wind intermittency include augmenting current levels of spinning and standing reserve and increasing the use of fast-response peaking plant, demand side management and storage [6, 12], [13]. These measures act over different timescales ranging from seconds to several hours. As different thermal generators have widely varying start-up and no-load costs, the optimal mix of thermal plant, storage, and interconnection to complement large-scale wind generation also depends not only on the distribution of run times but also the number of start-ups required. Therefore, characterising not only the occurrence but also duration of periods of continuously low wind speeds will be of key importance in determining the precise mix of complementary generation technologies needed to address wind variability as the penetration of wind generation increases.

Knowledge of the local wind speed distribution is important for matching wind turbine types to the available site wind resource [14, 15]. A frequency distribution such as the Weibull distribution [16] is widely used and has been found to fit the empirical wind speed distribution well in many cases, however temporal information is lost when such frequency-based methods are used. Specifically, the autocorrelation properties of the original time series cannot be inferred from a frequency distribution and, as Deaves and Lines have stated, it is not possible to determine the likelihood of extended periods of low winds directly from wind speed frequency distributions [17]. Such events, even if rare, introduce additional uncertainty to wind resource assessments and this is significant for developers as projects perceived as being more risky are less likely to be financed.

Datasets derived from actual wind generation values (e.g. [18]) are useful for simulating wind generation in power system studies but are contaminated with scheduled and unscheduled outages, which are difficult to distinguish from low wind events. A detailed wind resource assessment was prepared for Ireland based primarily on reanalysis of weather forecasting model outputs [19]. This produced good agreement with surface measurements, but the aim of the exercise was to produce estimates of mean wind speeds rather than to represent wind variability. Therefore surface wind speed measurements have been chosen as the basis for this study. As most of the wind generation capacity in Ireland was installed since 2000 there are few continuous wind generation records extending back to the mid-1990s, therefore their spatial representivity is limited. Even when data from several wind farms are aggregated, the issue of changing spatial distribution over time remains. In some cases such records may be more prone to local influences (e.g. terrain effects) than wind speeds recorded at properly situated meteorological stations.

Archer and Jacobson [20], Boehme and Robinson [21] and Cellura et al. [22] have demonstrated the feasibility of using measurements from networks of surface meteorological stations to extrapolate wind speeds and thus wind energy resources over wide areas. Previously, periods of continuously low wind speeds at measurement locations in the United Kingdom have been analysed for the purpose of estimating plume dispersion following accidental releases of airborne pollutants [17, 23]. The studies found that completely calm conditions were rare, but that low surface wind speeds ($< 2.4\ ms^{-1}$) occurred typically 20-30% of the time. A more recent study of the temporal variability of the aggregate UK wind resource based on over 30 years of surface wind speed measurements from 66 stations found that the simultaneous occurrence of low wind speeds across 90% or more of the UK was only one hour per year on average [10].

The study of periods of low winds can be considered as analogous to the study of low flows in hydrology. Wind speeds and river flows share the characteristics of being zero-limited and non-normally distributed. The technique of runs analysis [17, 24] can be used to examine the occurrence frequency of prolonged periods of values falling below a given threshold in a time series. Another widely-used technique, intensity-duration frequency analysis combines information on the duration of events with their recurrence frequency and has been applied to both high and low river flows as well as to heatwaves and gust wind speeds [24, 25, 26].

The aims of this paper are:

1. To introduce two techniques for the analysis of prolonged periods of low wind speeds from meteorological records.
2. To use these techniques to examine variability in the wind regime over Ireland, with particular emphasis on the occurrence of prolonged periods of low wind speeds, and the potential effects on energy yields from wind generation.

2. Data and methods

2.1 Data

Long term records of hourly surface wind speeds and directions from fourteen geographically dispersed stations in the Republic of Ireland were studied, starting from 1980. The temporal coverage of the data is illustrated in Table 1. Before 1990, wind speeds at most locations were measured using Dines pressure-tube anemometers. From the early 1990s most of the Dines anemometers were replaced by cup anemometers, however Dines anemometers continue to be used at Malin Head and Belmullet (L. Keegan, pers. comm.). Measurements are made at an effective height of 10 m above ground at all stations except Malin Head where measurements since 1977 have been made at 21 m above ground [27]. The stations are generally located at well-exposed sites, representative of their surrounding areas and the data has been widely used in the wind energy industry as the basis for measure-correlate-predict analyses. Speeds are reported by Met Éireann to the nearest knot (0.514 m s^{-1}). As the generation schedule is determined by the Irish electricity market operator on a daily basis, based on a half-hourly dispatch interval, wind variability will be analysed from the mesoscale into the synoptic range, i.e. from one hour up to several days.

2.2 Pre-processing

One problem that may arise when dealing with long meteorological series is the inhomogeneity of data. Stations may have been moved during the period of available records, and some instruments have been changed. Therefore the wind data series were tested for homogeneity before further analysis was undertaken. Firstly, time series of mean annual wind speed were calculated for each location.

These were then tested for trend and change points using non-parametric test statistics. The Mann-Kendal test [28] was used to detect trends, and the Pettitt-Mann-Whitney test was used to detect change points [29]. An indication of a trend or a change point suggests that there was either a change in exposure, instrumentation or a shift in the underlying climate at a particular station – slow changes such as adjacent tree growth should be indicated by a trend, while abrupt changes such as the erection of buildings or changes in instrumentation should be indicated by change points. The wind data were then binned by 30° wind direction sector and the annual frequency of values falling in each sector was calculated. This facilitated more detailed investigation of long term changes in individual sectors, and cross-checking with local changes indicated in the accompanying metadata such as land cover change or the construction of buildings adjacent to the station. Any missing values were treated as gaps and ignored. As this study aims to identify intervals with sustained low wind speeds, any attempt to interpolate for gaps would reduce the accuracy of the results.

The power law was used together with the modelled wind shear exponents for each station published in the European Wind Atlas [1] to extrapolate from the measurement height to 80 m, which we have assumed as a nominal hub height for utility-scale wind turbines in Ireland. Finally, a composite timeseries was derived, containing, at each time point, the maximum value of wind speed over all fourteen wind measurement locations, $v_{max}(t)$ (Eqn. 1). This timeseries was used to examine the occurrence of simultaneous low wind conditions across the entire country. Any period where the maximum wind speed remains below a certain threshold will correspond to simultaneous low wind generation output across the entire power system.

$$v_{max}(t) = max\{v_1(t), v_2(t), v_3(t), \dots\ v_{14}(t)\} \quad \text{[eqn. 1]}$$

2.3 Runs analysis

The frequency of occurrence of low wind speeds can be calculated in a similar means to the calculation of low flows in the study of hydrological systems, e.g. [24]. In this field of study, flow duration curves are often used to illustrate the probability of occurrence of flows below a range of threshold values. The analogue in electrical power systems analysis is the load duration curve. However, these approaches rely on binning all measured data by their magnitudes, and do not preserve temporal information [17], [24]. Therefore, alternative methods are necessary to identify *continuous* periods of below-threshold wind speed.

Long periods of low wind speeds in the preprocessed, vertically extrapolated series were identified in the records through the technique of runs analysis. In order to perform the runs analysis, a threshold wind speed, v_t, has to be selected first. Then the entire record is compared against the threshold. Values falling before the threshold are identified, and the durations of periods of sustained below-threshold speeds are recorded. The cumulative percentage frequency of wind speed remaining consistently below the threshold may then be calculated for any duration of interest [17].

Three thresholds were selected. The lowest threshold of 4 m s^{-1} corresponds to a nominal wind turbine cut-in speed, below which power output is negligible (e.g. [30]). The highest threshold (10 m s^{-1}) corresponds to a nominal wind speed for a turbine to develop rated power. Therefore at wind speeds below this threshold, wind generation is less than the maximum achievable by the turbine. An intermediate threshold of 6 m s^{-1} was also included, in order to assess the sensitivity of the results to threshold choice. The intermediate threshold speed corresponds to a low power output, approximately 15% of rated power in the case of the widely-installed Vestas V90 turbine [30]. Persistence was calculated over intervals of 1, 2, 4, 6, 8, 12, 16, 24 and 32 hours.

2.4 Intensity-duration-frequency and event seasonality

Complementary to the runs analysis, intensity-duration-frequency methods allow return periods to be calculated for events of specific magnitude and duration from long series of measured values. Return periods are calculated for low wind speed events by means of intensity-duration-frequency analysis. The goal is to produce a relationship describing the magnitude of an occurrence of prolonged low wind speeds as a function of the event duration D and the recurrence interval or return period T_r.

In order to produce the relationships, the following procedure was followed. A set of durations, D, of interest was defined as D = 10, 12, 16, 24, 36, 48, 96, 168, 240 and 480 hours. Moving averages of the hourly time series of wind speeds were calculated over different windows, the window widths being the same as the values of D. From these time series of moving averages, annual minimum values v_D were calculated over the full record. Therefore, each value of v_D represents the lowest value of wind speed averaged over D hours in a particular year. The approach is similar to that employed by Khaliq et al. [25] for calculating heatwave duration and frequencies from daily maximum temperature records.

Extreme value statistics were then used to calculate return periods T_r for the observed values of v_D. Fits of the type I extreme value distribution (also known as the Gumbel distribution) were carried out using the statistical toolbox of Matlab (Mathworks, USA), which provides maximum likelihood estimates of the parameters of the distribution. The type I extreme value distribution is widely used to model the behaviour of the tails of exponentially distributed quantities [31]. The cumulative probability distribution function of the type I extreme value distribution for smallest values of a quantity x is given by

$$_1G(x) = 1 - \exp(-\exp(y)) \qquad \text{[eqn. 2]}$$

where y is the reduced variate, $y = \alpha_n(x - u_n)$, with α_n and u_n determined from the smallest value in the sample.

Return periods for events of different magnitudes can then be calculated using the relation

$$T_r = 1/F(x) \qquad \text{[eqn. 3]}$$

which states that the return period or recurrence interval T_r for an event of magnitude equal to or less than x is the reciprocal of the probability of subceedance of x. Here, $F(x)$ is the initial (cumulative) probability distribution function of x. For extreme values of x, ${}_1G(x)$ (cf. eqn. 2) is often found to be a good fit to $F(x)$. Intensity-duration-frequency relationships for a given return period T_r and duration D can then obtained by fitting a curve to the observed values of v_D as a function of event duration D,

$$v_D(D) = a + b \ln (D) \qquad \text{[eqn. 4]}$$

where a and b are parameters determined through curve fitting.

Finally, in order to assess the seasonal occurrence of widespread low wind events, the 50 lowest wind speed events of one day and ten days' duration were selected from the v_{max} series. The dates of these events were then examined, and the number of events falling into each month of the year counted. This gives a picture of the monthly distribution of low wind speeds across the study area as a whole.

3. Results

3.1 Data quality control checks

The results of the tests on the data are summarised in Table 1. Cork Airport, Malin Head, Mullingar and Valentia stations all showed significant decreasing trends in mean annual wind speeds (over all sectors). Change points in the mean annual wind speed time series were indicated for Casement (1994), Cork Airport (1990), Birr (1995), Dublin Airport (1997), Mullingar (1994), Malin Head (1999) and Valentia (1992). The changes at Cork Airport and Dublin Airport may be due to construction or changes to instrument sites in these locations. Change points and trends were indicated in other stations for individual wind sectors. Based on the results of the data checks and dates of replacement of some of the Dines anemometers by cup anemometers, the years 1995-2008 were chosen as the best period for subsequent analyses. No known changes in instrumentation correspond with the calculated change points in mean annual wind speeds during this interval. A large amount of data was missing for Rosslare between 1996 and 1999, therefore those years were omitted for that location.

In runs analysis, gaps become more significant at longer durations, because any single missing value will affect multiple, overlapping aggregation windows. Thus, the presence of gaps may lead to large numbers of missing intervals at the longer aggregation levels. Therefore, the monthly distribution of gaps was calculated for each station. Although the incidence of gaps is considerable at some stations (e.g. up to 10% of hourly values are missing in some years at Belmullet), in general gaps are either very few in number or else evenly spread throughout the year.

3.2 Persistence of low winds

Figure 1 shows the probability of sustained low wind speeds over several durations from 1 to 32 hours for all measurement locations. Results are shown for each of the three selected wind speed thresholds of 4, 6 and 10 m s^{-1}. The figure illustrates the rapid fall-off of the occurrence of persistently low wind speeds as the duration of interest increases. Over short durations of one to four hours, wind speeds remain continuously below 10 m s^{-1} for over 50 % of the time in inland locations such as Kilkenny, Birr, Clones and Mullingar. At coastal locations, particularly in the northwest (e.g. Malin Head, Rosslare, Belmullet) the proportion of time with wind speeds persistently below 10 m s^{-1} is lower than 50% at all durations**.** Figure 1 also indicates that wind speeds rarely remain below 6 m s^{-1} for longer than 12 hours in most of the coastal locations. However, at all stations wind speeds below 10 m s^{-1} persist over 32 hours for a considerable percentage of the record. The persistence results for the intermediate threshold are also presented in the form of a contour map of the percentage of time occupied by wind speeds continuously below 6 m s^{-1} (Figure 2).

3.3 Event intensity duration frequency & seasonality

Intensity duration frequency relationships for low wind speeds were developed for each measurement location and used with Eqn. 4 to calculate the magnitudes of low wind speed events for a chosen duration of 20 days and a return period of 10 years. The power curve of the Vestas V90 turbine was applied to the velocity time series of each location to generate a corresponding power time series. The results of an intensity duration frequency analysis of the power time series are displayed as a contour map in Figure 3. Power is expressed as a fraction of rated power, i.e. P/P_{max}. An intensity-duration-frequency curve for the v_{max} timeseries is presented in the plot of Figure 4 for a ten-year return period.

The seasonal pattern of one-day and 20-day prolonged low values of v_{max} is illustrated by Figure 5. Events of one day duration are seen to occur during every month of the year, with a slightly higher frequency in July, August and September. The occurrence of low wind speed events of ten days duration exhibits a more marked seasonal pattern, with the highest occurrences during the month of July and relative infrequent occurrences between October and March.

4. Discussion

4.1 Low wind persistence from runs analysis & implications

In general, stations near coasts displayed the least frequent occurrence of persistent low winds. Considering the highest chosen threshold of 10 m s^{-1}, wind speeds at some of the inland locations such as Birr and Mullingar do not often exceed this value, as illustrated by occurrences of persistent below-threshold wind speeds above 50% of the time at durations of up to eight hours (Figure 1). Large-scale wind energy generation with standard hub heights and turbines will offer poor energy yields in areas represented by these stations, except perhaps in locations with favourable topography, such as well-exposed hills. The problem can be somewhat mitigated by selection of appropriate turbine types suited to lower wind speeds, but even at the lower threshold values of 4 and 6 m s^{-1}, the persistence of low wind speeds remains high relative to coastal sites. This would lead to very frequent sustained periods of generation well below rated power, occupying 10-20 % of the time, or every 5-10 days on average.

Several of the coastal stations (particularly Belmullet, Rosslare and Malin Head) have much lower occurrences of sustained wind speeds below the 10 m s^{-1} threshold, indicating more suitable conditions for utility-scale wind generation. These locations are less likely to encounter prolonged periods of low wind speeds, as shown by the occurrence probabilities of less than 50% for durations longer than 4-6 hours in some of the best locations (e.g. Belmullet) and will therefore exhibit higher capacity factors. However, wind speeds remain continuously below typical turbine cut-in for 24 hours between 2% and 6% of the time, depending on the location, i.e. a continuous, 24 hour low wind event will be experienced on average once every 16-50 days.

It is informative to compare the results with those obtained by Deaves and Lines at the coastal station of Camborne in southwestern England [17]. The largest threshold examined at Camborne of 6 knots is approximately equal to 4 m s^{-1} when extrapolated to 80 m, and the occurrences of one hour (c. 20% at Camborne; 22% at Cork) and ten hour (5% at both Camborne and Cork) periods of wind speeds remaining continuously below this threshold are similar at both stations.

4.2 Duration and frequency of low wind speeds and implications

A 20-day period with wind generation output never exceeding 15% of rated output is expected to occur once every ten years in locations with good wind resources such as Belmullet, Rosslare or Dublin Airport, and the occurrence of such an event would be equivalent to a reduction of almost 5% of the average annual energy yield from a wind farm at one of those locations, based on an assumed average capacity factor of 30%. At inland locations, particularly Mullingar, the 20-day low wind generation level is much lower, at 5% of rated output. The corresponding values at the western stations of Valentia and Shannon are lower than those found at other coastal locations. This is thought to be due to a more seasonally variable wind climate, with a higher range of mean wind speeds between the summer and winter months.

Widespread low wind events, identified by runs analysis from the multi-station maximum time series, $v_{max}(t)$, are ranked in order of severity in Table 2. Wind speeds during one of these events, the lowest wind speed event over 96 hours' duration which occurred in August 2005 (Table 2), are plotted together with total system wind generation in Figure 6. The total amount of installed wind generation on the Republic of Ireland system at this time was approximately 420 MW, and the figure shows that the total system wind power output was close to zero over the four day period. Total system wind generation was plotted against simultaneous values of v_{max} from 2008 in Figure 7 in order to illustrate the relationship between the two quantities.

Figure 4 shows that a widespread, four-day, sustained interval of wind speeds remaining continuously below 6 m s^{-1} has a return period of ten years. Total system wind power output is likely to remain below 15% of installed capacity throughout such an interval, and this estimate should be regarded as very conservative, given that the maximum value of wind speed over all fourteen measurement locations, including areas with low levels of installed wind generation, was used in its derivation. Sustained, four day or longer, periods of low wind generation from the expected 5800 MW of installed capacity on the 2020 system should therefore be rare and maintaining a capacity margin equivalent to the full wind generation capacity would be unnecessary. At the maximum duration studied, 20 days, the 10-year widespread low wind speed event magnitude is approximately 9 m s^{-1}, which although below the level for rated power output for most large turbines, would still correspond to a considerable level of generation.

4.3 Seasonality

The seasonal distribution of widespread occurrences of low wind speeds, as illustrated by Figure 5, shows that the summer and early Autumn months offer large potential windows for the scheduling of major wind farm outages of several days' duration for operations and maintenance, but opportunities for maintenance operations that can be carried out in 24 hours or less occur throughout the year. The peak months for prolonged low wind speeds do not correspond with the months of peak electricity demand (December to February), which decreases the overall system capacity margin requirement under high wind penetration.

4.4 Errors and uncertainty

Some of the limitations of the approach taken in this study include the hourly time resolution of the data, which gives the possibility of unrecorded threshold exceedances at timescales of less than one hour. However, in the case of capacity value calculations, the sensitivity to the temporal resolution of data has been shown to be very low for resolutions of one hour or less [32]. Vertical extrapolation also introduces uncertainty, as no estimation has been made of diurnal or seasonal variations in wind shear. The increased prevalence of stable atmospheric conditions and vertical stratification at night may lead to underprediction of nocturnal wind speeds at hub height by simple vertical extrapolation methods [19]. The results presented in the contour maps (Figure 2; Figure 3) refer to the unconstrained wind resource and should be interpreted with reference to local terrain and roughness conditions, and it should also be borne in mind that they are produced from a limited number of recording locations. Deaves & Lines [17] caution that when the large-scale forcing mechanisms for wind are weak, then local effects such as sea breezes, anabatic or katabatic winds may become significant. Some of the coastal sites in this study will undoubtedly have sea breeze effects, but as most stations are located in relatively flat terrain, anabatic or katabatic winds are unlikely to be a significant factor in our results.

Some designs of cup anemometer are known to have a high start-up inertia which can lead to overestimation of low wind persistence at speeds below 6 knots (approximately 3 ms^{-1}) [17], [33]. However, the cup anemometers used in the records examined in this study are of the lightweight type manufactured by Vaisala (Finland) or Vector Wind (UK) with low startup inertia and therefore should record low wind speeds accurately [17]. The Dines anemometer, a pressure-based instrument, does not suffer from such inertial effects and the model supplied by R. W. Munro Ltd. of Woodford Green, UK, has a quoted accuracy of 2 mph or less than 1 $m\ s^{-1}$.

5. Conclusions

The occurrence of prolonged periods of low wind speed cannot be inferred from mean wind speeds and is not explicitly represented by frequency distributions or load duration curves. Runs analysis and intensity-duration-frequency relationships have been demonstrated here as useful tools to analyse the persistence of low wind speeds in Ireland. It has been demonstrated that even a single event with a return period of ten years in an area with a favourable wind regime can reduce the annual energy yield of a wind farm by 5 %. Wind speeds in the least favourable areas for wind generation in the midlands often remain below typical turbine cut-in speeds continuously for several hours at a time. However, widespread, sustained low wind events across the whole country, corresponding to continuous low system wind power output for periods of several days, are comparatively rare. It is recommended that the accuracy of mediumrange numerical weather prediction models be studied in relation to predicting the time, rate of onset and duration of such events in order to provide system operators with adequate notice to economically schedule and manage reserve generators. A further benefit of such forecasts would be to assist wind farm operators in the scheduling of maintenance outages.

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	Mean annual wind speeds (all sectors)		Sectoral mean annual wind speeds	
Location	Trend detected	Year of change point	Trend detected and sector	Year and sector of change point
Belmullet			Incr: 300-330	
Birr		1995	Incr: 300-330	1997 (300-330)
Casement	Decr.	1997		
Claremorris			Decr: 330-360	2000 (240-270); 1999 (270-300)
Cork Airport	Decr.	2003	Decr: 0-30	1996 (0-30)
Clones				1997 (180-210)
Dublin Airport	Decr.	1997	Decr: 0-30 Decr: 180-210 Incr: 270-300	1994 (90-120); 1997 (270-300),
Knock				
Kilkenny				
Malin Head		1994		
Mullingar				
Rosslare				
Shannon			Decr: 330-360	2000 (90-120);
Valentia			Incr: 120-150 Incr: 150-180	2000 (120-150); 2000 (150-180)

Table 1. Results of overall and sectoral data quality control checks for trend and change points. Statistically significant trends are indicated as increasing or decreasing; years of detected change points are given. Sectors are labelled by compass bearing in degrees.

12 hours		24 hours		96 hours		480 hours	
Date	v (m s-1)	Date	v (m s-1)	Date	v (m s-1)	Date	v (m s-1)
Sep 22,2001	2.8	Sep 22,2001	3.6	Aug 10,2005	6.1	Jul 31,2000	9.2
Oct 15,2009	3.2	Oct 15,2009	4.1	Oct 15,2009	6.2	Feb 26,2009	9.4
Jun 24,1999	3.7	Dec 02,1998	4.9	Jul 19,2000	6.4	Aug 19,2005	9.7
Dec 02,1998	4.2	Aug 08,2005	4.9	Nov 12,1999	6.4	May 24,2001	10.0
Apr 14,1995	4.2	Mar 31,2000	5.1	Jun 01,2008	6.5	Jul 27,1997	10.1

Table 2. Ranked lowest all-station maximum wind speed events over four durations of 12, 24, 96 and 480 hours.

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Figures

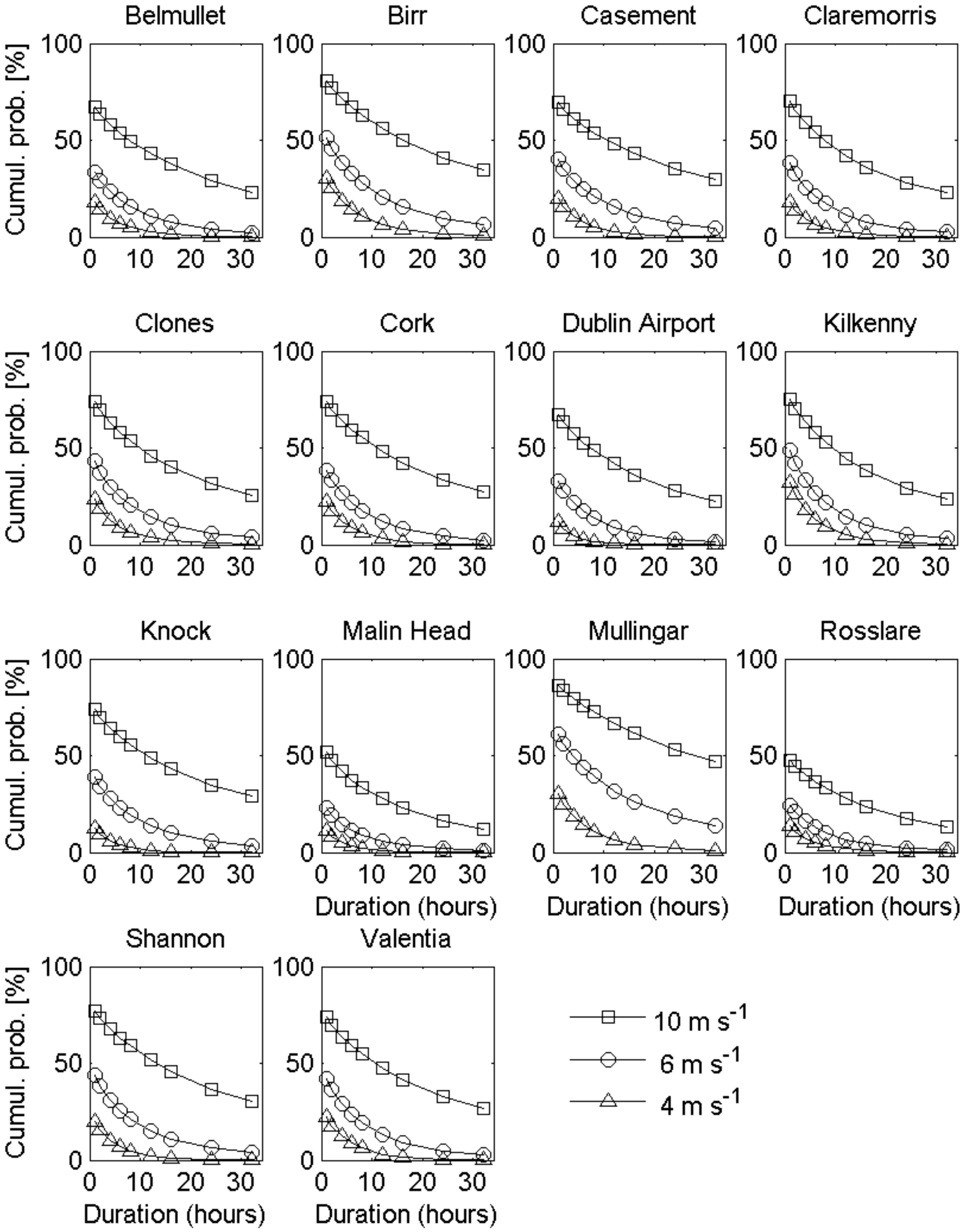

Figure 1. Cumulative probabilities of persistence of extrapolated 80 m wind speeds remaining below thresholds of 4, 6 and 10 m s^{-1} at the 14 measurement locations over several durations from 1 to 32 h.

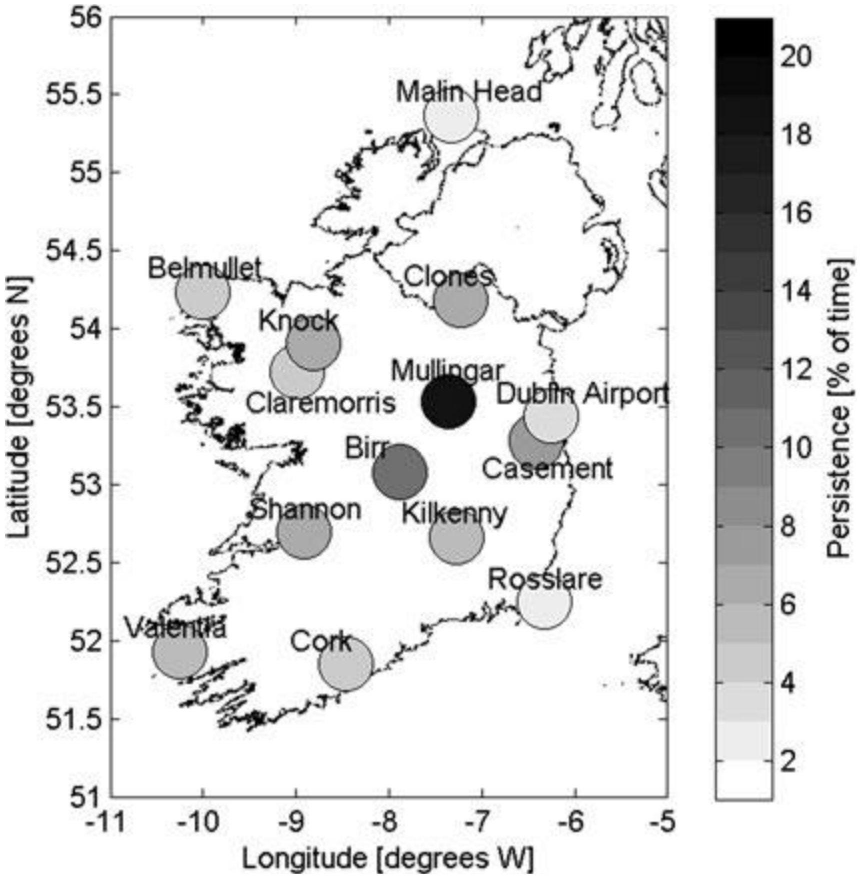

Figure 2. Map showing the occurrence (% of time) of low wind speed conditions (winds persistently below 6 m s^{-1} for 24 h or longer) at the measurement locations.

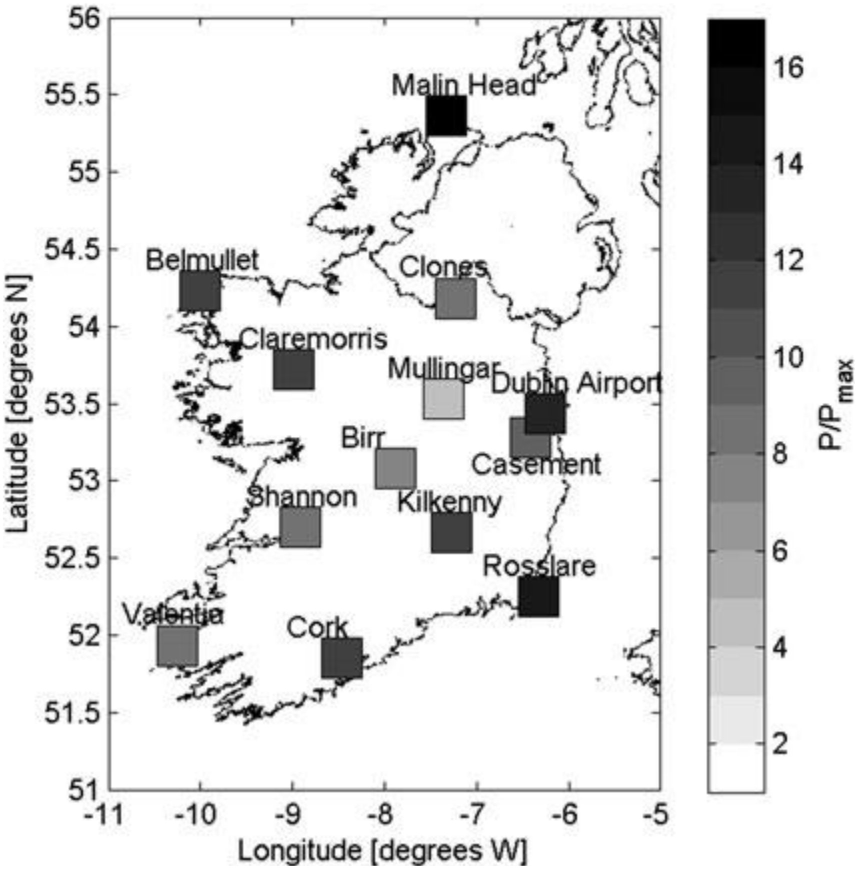

Figure 3. Map of the 20-day (480 h) low wind power level (expressed as a fraction of maximum achievable power by using the Vestas V90 turbine at 80 m height) at the measurement locations with an expected recurrence interval of 10 years.

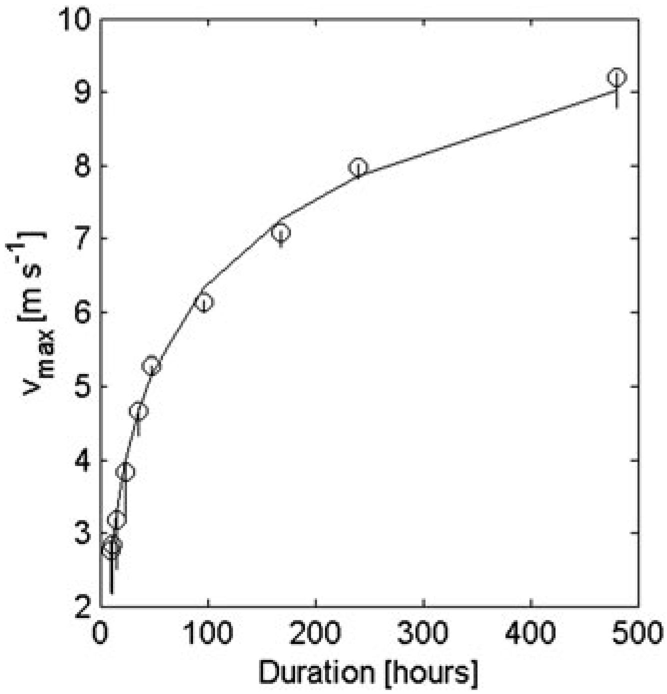

Figure 4. Intensity–duration curve for vmax, describing continuous, widespread low wind events with a 10-year recurrence interval over several durations up to 20 days. Vertical lines indicate the extent of the 95% confidence interval indicated by the maximum likelihood fit.

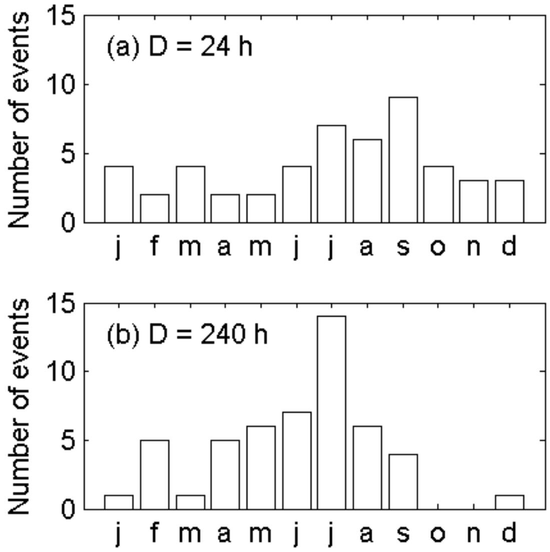

Figure 5. Monthly distribution of the lowest wind speed events in the v_{max} time series of (a) 1 and (b) 10 days' duration.

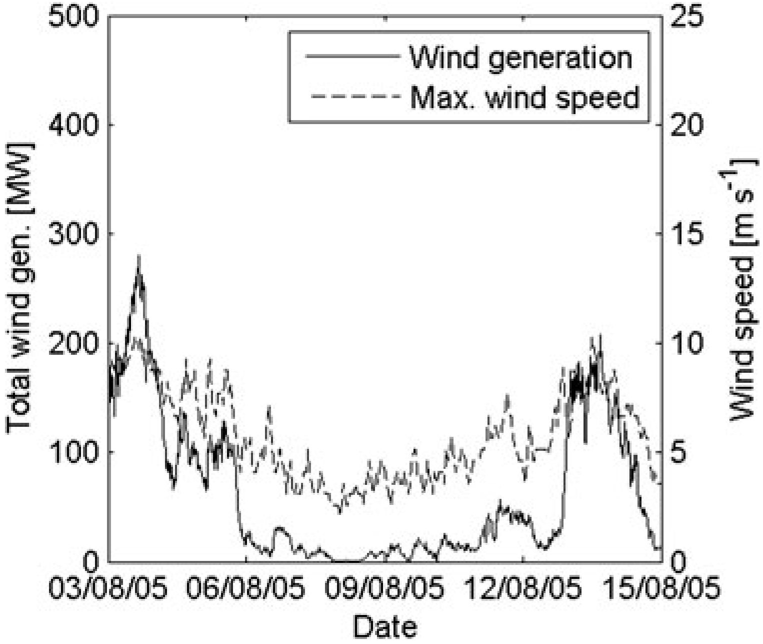

Figure 6. Sustained low wind speeds and low total system wind generation between 6th and 11th of August 2005.

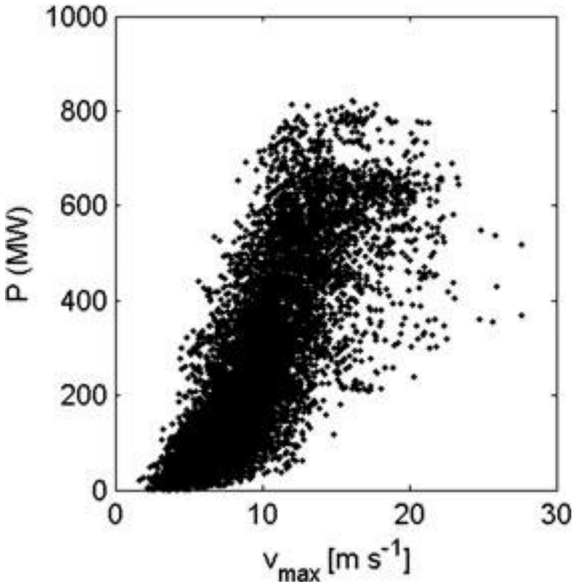

Figure 7. Total wind generation on Ireland system versus maximum observed wind speed for 2008.