A weather regime characterisation of Irish wind generation and electricity demand in winters 2009–11

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Abstract

Prolonged cold spells were experienced in Ireland in the winters of 2009–10 and 2010–11, and electricity demand was relatively high at these times, whilst wind generation capacity factors were low. Such situations can cause difficulties for an electricity system with a high dependence on wind energy. Studying the atmospheric conditions associated with these two winters offers insights into the large-scale drivers for cold, calm spells, and helps to evaluate if they are rare events over the long-term. The influence of particular atmospheric patterns on coincidental winter wind generation and weather-related electricity demand is investigated here, with a focus on blocking in the North Atlantic/European sector. The occurrences of such patterns in the 2009–10 and 2010–11 winters are examined, and 2010–11 in particular was found to be unusual in a long-term context. The results are discussed in terms of the relevance to long-term planning and investment in the electricity system.

1. Introduction

Output from wind farms in the Republic of Ireland peaked at over 2.4 GW in February 2017 (EirGrid 2017), whilst the annual peak (winter) electricity demand has typically been between 4.5 and 5.0 GW in the last 6–7 years (EirGrid 2015). The electricity system on the island of Ireland is linked to that of Great Britain (GB) via two interconnectors with a total capacity of 1 GW. At any given time, the Irish grid can accept up to 55% of power from a combination of wind generators and interconnection (O’Sullivan et al 2014). Given the simultaneous dependence of wind generation and system demand on weather conditions, it is possible that situations can occur where wind generation is low whilst demand is high, and as wind penetration increases, this could be problematic. Understanding the risk of such situations in the long-term allows for better system planning, whilst their predictability at medium-term influences the management of the system.

Winter 2009–10 (09–10) was notably cold over the British Isles, whilst wind speeds were lower than average. This combination could have resulted in strain on the electricity supply system but Leahy and Foley (2012) conclude that, in fact, the impact on electricity demand in Ireland was lower than expected due to coincidental holidays and a period of economic recession. Brayshaw et al (2011a) found that during a very cold and calm spell in January 2010, very low aggregate wind generation for the whole of GB (dominated by Scottish wind farms) coincided with high demand for electricity. The cold spells of the following winter of 2010–2011 (10–11) were actually more severe in terms of persistent low air temperatures. Met Eireann (2010) reported that December 2010 experienced the ‘coldest weather over Ireland since 1963’, whilst the Irish electricity transmission operator, EirGrid, reported its highest ever demand on 22nd December 2010 (EirGrid 2017).

Because wind generation is a relatively new phenomenon that has grown rapidly, and because electricity demand is subject to various socio-economic and technological influences, historical records are not relevant beyond the recent period and are, therefore, not well-suited for analysis. By examining
the long-term atmospheric patterns associated with unfavourable conditions for the electricity system and analysing their occurrences, it may be possible to develop a better understanding of the prevalence of critical cold/calm conditions over a longer period, whilst also furthering knowledge of the associated large-scale climate drivers.

Very cold winter temperatures accompanied by low wind speeds are often attributed to persistent high pressure systems over the British Isles, described as a ‘low wind cold snap’ and discussed in Gross et al (2006). Brayshaw et al (2011a) argue that, although the ‘high-over-Britain’ situation typically leads to low wind speeds, such conditions are only ‘moderately susceptible’ to very low temperatures, and that many of the peak demands over the last 20–30 years have occurred as a result of a persistent high pressure system lying to the north of the British Isles or over Scandinavia. Thornton et al (2017) identified that for the UK, the highest daily demand levels are related to ‘the building of a high pressure to the north of GB’, but that during these periods, average wind power capacity factors are not at their lowest.

While Thornton et al (2017) use mean sea-level pressure to classify weather patterns relating to wind and demand in GB, Grams et al (2017) derive a set of weather regimes by clustering geopotential height fields into a number of categories, to understand fluctuations in wind power throughout Europe. At a scale of days to weeks, the authors find that different countries incur highs and lows at different times, with ‘blocking’ type regimes associated with lower wind capacity factors for Ireland. The term ‘blocking’ in relation to the European mid-latitudes refers to situations where the typical pattern of westerly flow and its associated weather is disrupted by the presence of a stationary or slow moving anticyclone at higher latitudes, and a stationary low pressure area to the south (Treidl et al 1981, Trigo et al 2004). This forces a change to a meridional flow pattern over mid-latitude regions of Europe. Trigo et al (2004) report that in Ireland, the daily temperatures for blocked (non-blocked) conditions are around 0.4 °C–0.8 °C below (above) average with a prevailing north-easterly (westerly) wind. The authors also calculate that around 4–6 fewer cyclones, associated with very high wind speeds, occur per winter over Ireland under blocked conditions than under non-blocked conditions.

In this study, the aim is to understand the large-scale atmospheric patterns linked to the high demand, low wind winters of 09–10 and 10–11 in Ireland, and whether they were unusual over the longer-term. The relationship between winter wind generation and electricity demand in Ireland is first explored. The occurrence of typical winter weather regimes, determined according to geopotential height anomalies, is related to both wind generation and demand patterns. The 2 dimensional patterns of persistent blocking over the North Atlantic and Europe during the cold winters are then compared to historical occurrences, including other years with low wind/high demand.

2. Data and methods

2.1. Data

Throughout the study, a number of datasets have been used:

- EMHIRES European wind energy generation simulation 1986–2015 (González-Aparicio et al 2017)
- EirGrid 15 m inutely reported demand (MW), 2007–2015, (EirGrid 2016)
- Met Eireann weather data recorded at Dublin and Cork Airports, 1942–2015, (Met Eireann 2016)
- 20th Century Reanalysis V2c geopotential height data at 500 hPa for the period 1940–2014 (Compo et al 2011) provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from www.esrl.noaa.gov/psd/.

2.2. Joint analysis of wind generation and weather-related demand

The distributions of daily wind generation capacity factor and weather-related demand for winter months of October–February in the period 1986–2014 are examined both individually and jointly, to understand their coincidence.

In order to capture a 30 year period of wind generation on a consistent basis, data for the Republic of Ireland taken from a European wind energy generation model (González-Aparicio et al 2017) are used here, which combines reanalysis data with a statistical downscaling technique. The method is applied at locations of wind generation capacity operational in 2015, and assumes that it has been operational since 1986. The dataset has been verified against records and represents an improvement on similar but less sophisticated datasets, e.g. Cradden et al (2017), Cannon et al (2015).

2.2.1. Constructing weather-related demand time series

Electricity demand data also contain non-weather-related components, including seasonal factors, economic influences and, over a longer period of time, the impact of different technologies—e.g. the move away from incandescent lightbulbs. The weather-driven components relate mainly to lighting and space heating/cooling. Approximately 7% of domestic space heating in the Republic of Ireland is provided by electricity, but this figure rises to between 15% and 30% in some urban areas (Ordnance Survey Ireland and Central Statistics Office 2017). Cooling is not thought to be a significant factor.

The sensitivity of electricity demand to air temperature for a small number of large European countries, including GB has been analysed by the French transmission operator (RTE 2015). France has the highest sensitivity, with daily demand increasing by
2.4 GW per °C of temperature drop. For GB, the figure is approximately 1 GW per °C. Damm et al (2016) model the sensitivity of daily demand in 26 European countries to temperature, and find GB has a sensitivity of around 0.8 GW per °C and Ireland has a sensitivity of approximately 0.06 GW per °C. The average demand in GB is around 30 GW, compared to Ireland’s 3 GW, so the ratios of 2%–3% of average demand per °C are fairly similar.

A method to isolate the weather-related factors from total recorded demand, drawing on aspects of comparable models (Bloomfield et al 2016, Magnano and Boland 2007, Taylor 2003, Thornton et al 2016) is applied here. It consists of a multiple linear regression where demand is made up of a linear combination of variables representing influences including weather, seasonal and time-based factors (see supplementary material section 1 for details available at stacks.iop.org/ERL/13/054022/mmedia). The model has been constructed using reported demand data (averaged to daily mean5) for 2007–2015, a period considered to be short enough to exclude the influences of, for example, technological changes.

In order to reconstruct a time series of weather-related demand (WRD) for the period 1986–2015, a similar approach is taken as in Bloomfield et al (2016). The regression coefficients relating only to relevant weather components, along with those for a Tuesday–Thursday-type weekday, have been applied for all days. This removes the masking of peak WRD that will occur when very cold days fall at weekends or holidays. The October–February period was most well-fitted by the model (see supplementary material section 1), corresponding to time when space heating is in regular use, and thus the study focuses on these months.

2.3. Analysis of atmospheric patterns
Daily geopotential height anomalies at the 500 hPa level have been derived from the 20th Century reanalysis v2c interpolated from 2° resolution onto a 2.5° × 2.5° grid. The anomaly fields for the period 1940–2014 are clustered into four ‘weather regimes’ using a method based on k-means (Cassou 2010, Grams et al 2017, Yiou et al 2007). For each weather regime, the mean and variability of associated daily wind capacity factors and WRD are presented, and conversely, the distributions of weather regimes for particularly high WRD and low wind conditions are examined.

To study specifically the influence of blocking locations and the persistence of blocking events, using the methodology described by Rimbu and Lohmann (2011) and Scherrer et al (2006), two-dimensional maps of blocking frequencies over the area 80°W–40°E and 35°N–75°N have been derived for periods of interest based on gradients of 500 hPa geopotential height. Following the equations set out in the supplementary material (section 2) for each grid point, if the gradient over 15° in the northern direction is greater than zero, and the gradient over 15° in the southern direction less than −10 m/° latitude, the location is considered to be blocked. Both instantaneous and more persistent blocking events are considered in the context of associated wind production and demand conditions.

3. Results

3.1. Joint occurrence of weather-related demand and wind generation
The distributions of modelled Tuesday–Thursday type weekday WRD (presented as a fraction of the 99th percentile value) for each of the winters (October–February), 2005–06 to 2014–15, are compared in figure 1. Winters 09–10 and 10–11 show both the highest daily mean WRD and most extreme outliers, with
10–11 having more extreme values overall and a slightly higher mean. From previous years (1986–2005, not shown), other winters show daily outliers above 1.25 (1990–91, 1995–96) and above 1.5 (1986–87, 2000–01), but the means and maximum values are well below those of the 09–10 and 10–11 winters.

For wind capacity factors, figure 2, both the mean and median daily values for 09–10 and 10–11 were lower than for other winters in this period, and including years from 1986–87 onwards (not shown), there were no other winters with means, medians or 1st quartile values as low as these two winters.

Figure 3, left, shows evidence that higher daily winter WRDs are associated with lower than average capacity factors for the period 1986–2014. Figure 3, right, confirms this, giving the average capacity factor for all days when WRD (given as a fraction of the 99th percentile value, labelled WRD_{99}) is above a given threshold. Keane et al (2011) produced a similar plot for two years, 2007–2008, using total demand for GB and found that the capacity factors dropped approaching the peak demand, levelling off around 15%. Here, the capacity factors reduce from a winter average of 0.43 over all demands to around 0.21 when WRD is greater than the 99th percentile value. There is no evidence of a ‘recovery’ in capacity factors at the highest demand levels, as shown for GB by Thornton et al (2017).

Above 1.5 times the 99th percentile value, the majority of wind capacity factors are less than 0.2; these instances are highlighted in figure 4. December 2010 is responsible for most points, with November 2010, January 2010, December 2000 and January 1987 making up the rest. The two January 1987 points were related to a particularly cold spell affecting northern Europe, but with accompanying strong winds in Ireland (Met Eireann 1987). The 5 most extreme values all occurred in December 2010, indicating an unusually severe cold, calm spell in this period.

Figure 2. Boxplot of distributions of daily capacity factor for 10 recent winters. Green triangles = means, green lines = medians, black circles = outliers.

Figure 3. (Left) Bivariate histogram of winter weather-related demand and wind capacity factor 1986–2015. (Right) Mean capacity factor for increasing levels of weather-related demand: The x axis gives, WRD_{99}, the WRD as a fraction of the 99th percentile value. Solid line = mean capacity factor for all days with demand greater than WRD_{99}. Dashed line = fraction of hours where demand is greater than WRD_{99}.
3.2. Weather regimes

Weather regimes offer a useful framework to investigate the possible connection between WRD, wind capacity factors and large-scale atmospheric circulation and blocking patterns. The mean geopotential height anomaly patterns (weather regimes) and their occurrence frequencies as derived from the 20th Century reanalysis 500 hPa geopotential height are, as expected, very similar to those found in the aforementioned studies (Rimbu and Lohmann 2011, Scherrer et al. 2006) (figure 5).

Whilst there are discernible differences between the mean WRD and wind capacity factor for each weather regime, there is clearly a large amount of intra-regime variation (table 1). The Zonal Regime (Zo) has the highest wind capacity factors and the lowest WRD, and the lowest intra-regime standard deviation for both factors. Greenland Blocking (GrB) is associated with the highest WRD, but again with a high level of intra-regime variance. Atlantic Blocking (AtlB) is associated with the lowest mean wind capacity factors, and the highest variance.

The data can also be examined in the opposite way, identifying the regimes that are most prevalent during times where WRD or wind capacity factor are within a given quartile of their distributions. For wind (figure 6), increasing capacity factors are strongly associated with higher frequencies of Zo. The lowest wind quartile shows a high frequency of AtlB, followed by Scandinavian Blocking (ScB) and GrB.

With regard to WRD, there is a reduction in the zonal regime frequency and an increase in GrB in the last quartile of the WRD distribution, compared to the other three (figure 7). Focussing on the highest 10% of WRD (figure 8), the most prevalent regime is GrB, followed by AtlB. In summary, the ‘worst-case’ of the highest weather-related demand accompanied by low wind production seems most likely to occur in conjunction with Greenland or Atlantic blocking regimes.

Figure 9 shows that GrB was the most frequent weather regime in 09–10, followed by ScB. Winter 10–11 also had a high occurrence of GrB; the remaining regimes showed only small differences between their frequencies. Over the 1986–2014 period, no other winters had GrB as the highest frequency regime. Over the 75 years for which the reanalysis data have been examined, GrB was only the most frequent regime for 1978–79—a notoriously cold winter in the British Isles (Prior and Kendon 2011) (figure 9).
Figure 5. Weather regimes identified on the basis of mean geopotential height anomalies for each pattern (cluster ‘centroids’). Occurrence frequencies: 1. 26.7%, 2. 18.7%, 3. 32.0%, 4. 22.6%.

Table 1. Winter wind capacity factors and weather-related demands for each identified weather regime 1986–2014.

| Weather regime          | Mean wind capacity factor | Standard deviation of wind capacity factor as % of mean² | Mean WRD as % of long-term mean | Standard deviation of WRD as % of mean² |
|-------------------------|---------------------------|--------------------------------------------------------|-------------------------------|----------------------------------------|
| 1. Scandinavian Blocking (ScB) | 0.35                      | 57%                                                   | 98%                           | 40%                                    |
| 2. Greenland Blocking (GrB)   | 0.31                      | 61%                                                   | 127%                          | 50%                                    |
| 3. Zonal (Zo)             | 0.47                      | 38%                                                   | 89%                           | 30%                                    |
| 4. Atlantic Blocking (AtlB) | 0.28                      | 71%                                                   | 100%                          | 37%                                    |

² In effect, this is coefficient of variation.
3.3. Blocking

Given the link between low wind conditions, high WRD, and the ‘blocking’ types of weather regime, in this section the locations and persistence of blocking events in the North Atlantic and European regions are investigated, and how this impacted on the WRD and wind capacity factors in winters 09–10 and 10–11.

Maps have been created based on the number of blocked days at each location on the grid relative to the total number of days in the analysis period. The persistence of blocks is considered at 1 day, 3 day and 5 day levels; see supplementary material for images of maps at all persistence levels.

The climatological means for each of the persistence criteria are very similar in pattern, showing the recognised ‘T-bar’ shape identified in previous studies, e.g. Rimbu and Lohmann (2011), Scherrer et al (2006). Whilst the percentage of blocked days reduces as the persistence length criteria increases, this pattern remains largely the same.

Two subsets of winters have been extracted, neither including 09–10 or 10–11 as it is intended to compare these to the long-term average conditions. The first subset contains the union of the set of ten years with the lowest mean wind capacity factor and the set of ten years with the lowest 25th percentile of wind capacity factor. The second subset contains the union of the set of ten years with the highest 75th percentile WRD value and the set of ten years with the highest 90th percentile WRD value. In both cases there were two unique years in each of the groups, so 12 years were included in each set in total. Seven from the twelve years in the low wind and high WRD subsets are common to both groups.

The most persistent blocking events in the selected low wind years are found around the British Isles and North Sea. The five day blocking events for the high WRD years are concentrated in the area to the north of the British Isles and to the west of Norway, with a smaller peak over Greenland. Comparing high WRD and low wind years (figure 10), five day blocks to the north of the British Isles are more likely in high WRD years, and more likely to be centred over the British Isles in low wind years. The influence of persistent
Greenlandic blocks is less in low wind years but relatively important in high WRD years.

The five day blocks in 09–10 (figure 11, top) are most prevalent in between the Davis Strait and the southern tip of Greenland, with the area north of the British Isles and over Scandinavia being less accentuated. This correlates with the patterns found for other high WRD years, although the emphasis on persistent Greenland blocks is much stronger in 09–10. The pattern of blocking shows much less similarity to those for other low wind years.

In 10–11, the areas with the most frequent five day blocks (figure 11, bottom) are in the northern Davis Strait and to the west of Ireland, with a smaller level of activity over Greenland and France/Germany. The Greenlandic peak corresponds with other high WRD years, but the strong peaks to the west of Greenland and Ireland are unusual, as neither of these locations appear as high frequency areas in the climatological maps.

4. Discussion

The analysis presented here shows that, in the context of the last 29 years, the October–February periods of 09–10 and 10–11 had some extremely cold periods and were less windy than average, with 10–11 suffering the most extreme low temperatures. Table 2 highlights that both 09–10 and 10–11 had a much higher percentage of days with extreme WRD compared to the average, with the average wind capacity factor also being significantly lower in 10–11 during these extreme days compared with the long-term average. More than 50% of the winters categorised as high demand in section 3.3 were also categorised as having low wind, which is consistent with the results of figure 3.

A typically high-demand/low-wind winter in Ireland shows higher frequencies of Greenland and Atlantic blocking regimes. This is consistent with the findings of previous studies (Brayshaw et al 2011b, Grams et al 2017, Thornton et al 2017). Relating the findings to teleconnection patterns, the Greenland Blocking regime strongly resembles an NAO negative state, whilst a positive EA resembles the Atlantic Blocking regime. Previous work (Cradden et al 2017) indicated that the combination of negative NAO with positive EA gives rise to the lowest average wind generation capacity factors in Ireland, thus consistent with the weather regime based findings here. The zonal regime, with its strong similarity to NAO positive conditions, is clearly related to lower weather-related demand, i.e. higher air temperatures, in agreement with Comas-Bru and McDermott (2014), and higher wind capacity factors, as found in Cradden et al (2017).

Importantly, there is a high degree of intra-regime variance in WRD and wind capacity factor, similar to results found for GB (Thornton et al 2017), and so the predictive capability of these regimes with respect to the regular planning and operation of electricity systems at a seasonal level may require further consideration. In terms of identifying the likelihood of seasonal extremes, however, an analysis of weather regimes may be more informative. Both the 09–10 and 10–11 winters show a relatively high frequency of Greenlandic blocking, with 10–11 having a higher frequency of Atlantic blocking than 09–10. This is unusual; analysis of regimes since 1940 shows that no other winter showed a prevalence of Greenlandic blocking regimes except for 1978–79, also known to be particularly cold.

For low wind and high demand winters (not including 09–10 or 10–11) blocks are typically concentrated over the British Isles, Scandinavia and Greenland. For low wind winters, the most persistent blocks tend to be located immediately over the British Isles and the North Sea area, whilst for high demand winters, the persistent blocks are located north of the British Isles and to the west of Norway. This result correlates well with the findings of Brayshaw et al (2011b).
for GB. There is also a stronger tendency for frequent and persistent blocks to be located over Greenland in high demand winters compared with low wind winters.

In 10–11, the two main persistent blocking locations, to the far west of the Davis Strait and in the mid-Atlantic, are unusual, having a much lower frequency in the longer term climatology and in other high-demand/low-wind winters. This emphasises that the 10–11 winter was particularly unusual in terms of atmospheric patterns, and may explain the persistent cold spells and coincident low wind generation.
From the perspective of the electricity system operator, forecasting of events such as those of winter 10–11, particularly at a seasonal level, is critical to optimal management of the system. As predictions of atmospheric patterns improve, such as the winter NAO as discussed in Scaife et al (2014) and Dunstone et al (2016), they will be of significant benefit to grid operators. Considering further the relevance of this study to the Irish electricity system, there are subtleties that may become apparent with detailed analysis of the interconnections with GB. For example, there is currently a plan for extensive development of wind generation in the North Sea, to the east of GB (as discussed in Drew et al (2015)), which may be affected differently by some weather patterns compared to Ireland’s wind generators to its west; for example, Scandinavian blocking is likely to cause strong easterlies in the North Sea that may not reach the west of Ireland. It is possible in such cases, some of this GB wind power could become available for export, or vice-versa.

Further electrification of heating in Ireland will strongly increase the sensitivity of electricity demand to temperature, and exacerbate the imbalance in wind power and demand caused by conditions such as those found in winter 2010–2011. Heinen et al (2017) examined the investment costs of a future hybrid heating system utilising electricity when wind production is high, and gas when wind production is low. The model incorporates temperature and wind information to examine the coincidence of cold, low wind conditions. Data for the 2010–2011 winter indicated a case for significantly large investment. On the basis of the analysis presented here, atmospheric conditions during winter 2010–2011 are seen to be particularly unusual suggesting that any investment decisions based on this anomalous winter should be approached cautiously.

5. Conclusions

The winters of 09–10 and 10–11 experienced sustained periods of low temperatures, and lower than average seasonal wind generation output. There is evidence that the high prevalence of Greenlandic blocking regimes is related to the unusually severe conditions experienced. Furthermore, there were some patterns of persistent blocking in the mid-Atlantic and west of Greenland found in the 10–11 winter that are not evident in other high-demand/low wind winters. These persistent blocks may have resulted in particularly persistent low temperatures, and hence the high weather-related electricity demand of December 2010.

This work represents an improved understanding of how atmospheric circulation patterns relate to wind generation, weather-driven electricity demand, and their coincidence with respect to Ireland’s electricity system. It is important to note that although there are some strong relationships on average, there still remains a high degree of variation within individual seasonal results; the most useful aspect is in identifying the potential for more unusual extreme events in a given season. Such information is useful for the development of planning and investment models for electricity grids. Knowing that 2010–2011 was a particularly unusual occurrence is critical, for example, if it is to be included in such models.

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References

Bloomfield H C, Brayshaw D J, Shaffrey L C, Coker P J and Thornton H E. 2016 Quantifying the increasing sensitivity of power systems to climate variability Environ. Res. Lett. 11 124025

Brayshaw D J, Dent C and Zachary S. 2011a Wind generation’s contribution to supporting peak electricity demand—meteorological insights Proc. Inst. Mech. Eng. Part O: J. Risk Reliab. 226 44–50

Brayshaw D J, Dent C and Zachary S. 2011b Wind generation’s contribution to supporting peak electricity demand—meteorological insights Proc. Inst. Mech. Eng. Part O: J. Risk Reliab. 226 44–50

Cannon D J, Brayshaw D J, Methven J, Coker P J and Lenaghan D 2013 Using reanalysis data to quantify extreme wind power generation statistics: a 33 year case study in GB Renew. Energy 75 767–78

Cassou C.  2010 Euro-Atlantic regimes and their teleconnections Weather regimes: concept and definition North Atlantic-Europe weather regimes Proc. ECMWF Sem. on Predictability in the European and Atlantic Regions (6–9 September 2010)

Comas-Bru L and McDermott F. 2014 Impacts of the EA and SCA climate relationship Q. J. R. Meteorol. Soc. 140 354–63

Compo G P et al. 2011 The twentieth century reanalysis project Q. J. R. Meteorol. Soc. 137 1–28
Cradden L C, McDermott F, Zubiate L, Sweeney C and O’Malley M 2012 A 34 year simulation of wind generation potential for Ireland and the impact of large-scale atmospheric pressure patterns Renew. Energy 106 165–76
Damm A, Köberl J, Prettenthaler F, Rogler N and Toglohofer C 2016 Impacts of +2 °C global warming on electricity demand in Europe Clim. Serv. 7 12–30
Drew D, Cannon D, Brayshaw D, Barlow J and Coker P 2015 The impact of future offshore wind farms on wind power generation in GB Resources 4 155–71
Dunstone N, Smith D, Eade R, Robinson N, Andrews M and Knight I 2016 Skilful predictions of the winter North Atlantic Oscillation one year ahead Nat. Geosci. 9 809–14
EirGrid 2015 Historical wind generation and demand data
EirGrid 2016 Smart Grid Dashboard (http://smartgrid.dashboard.eirgrid.com/#/rois/wind) (Accessed: 9 December 2016)
EirGrid 2017 Smart Grid Dashboard
González-Aparicio I, Monforti F, Volker P, Zucker A, Caref F, Huld T and Badger J 2017 Simulating European wind power generation applying statistical downscaling to reanalysis data Appl. Energy 199 155–68
Grons C M, Beele R, Pfenninger S, Staffell I and Wernli H 2017 Balancing Europe’s wind-power output through spatial deployment informed by weather regimes Nat. Clim. Change 7 557–62
Gross R, Green T, Leach M, Skea J, Heptonstall P and Anderson D 2006 The Costs and Impacts of Intermittency (London: UK Energy Research Centre)
Heinen S, Turner W, Cradden L, McDermott F and O’Malley M 2016 Electrification of residential space heating considering coincidental weather events and building thermal inertia: a system-wide planning analysis Energy 127 136–54
Keane A, Milligan M, Dent C J, Hasche B, D’Ammunzio C, Dragoon K, Holtiten H, Samaan N, Soder L and O’Malley M 2011 Capacity Value of Wind Power Power Syst. IEEE Trans. 26 364–72
Leahy P G and Foley A M 2012 Wind generation output during cold weather-driven electricity demand peaks in Ireland Energy 39 48–53
Magnano L and Boland I 2007 Generation of synthetic sequences of electricity demand: application in South Australia Energy 32 2230–43
Met Eireann 2016 Display and Download Historical Data (www.met.ie/climate-request/) (Accessed: 8 January 2016)
Met Eireann 2010 Monthly Weather Bulletin, December 2010 (Irish Weather Reports)
Met Eireann 1987 Monthly Weather Bulletin, January 1987 (Irish Weather Reports) Met Eireann
Ordnance Survey Ireland, Central Statistics Office 2017 Permanent Private Households by Central Heating, Provinces (Census 2016, Theme 6.5, Ireland)
O’Sullivan J, Rogers A, Flynn D, Smith P, Mullane A and O’Malley M 2014 Studying the maximum instantaneous non-synchronous generation in an island system-frequency stability challenges in Ireland IEEE Trans. Power Syst. 29 2943–51
Prior J and Kendon M 2011 The UK winter of 2009/2010 compared with severe winters of the last 100 years Weather 66 4–10
Rimbu N and Lohmann G 2011 Winter and summer blocking variability in the North Atlantic region—Evidence from long-term observational and proxy data from southwestern Greenland Clim. Past 7 543–55
RTE 2015 RTE (Réseau de transport d’électricité), 2014 Annual Electricity Report (Paris)
Scaife A A et al 2014 Skillful long range prediction of European and North American winters Geophys. Res. Lett. 5 2314–9
Scherrer S C, Croci-Maspoli M, Schwierz C and Appenzeller C 2006 Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the Euro-Atlantic region Int. J. Climatol. 26 233–49
Taylor JW 2003 Using weather ensemble predictions in electricity demand forecasting Int. J. Forecast. 19 57–70
Thornton H E, Hoskins B J and Scaife A A 2016 The role of temperature in the variability and extremes of electricity and gas demand in GB Environ. Res. Lett. 11 114015
Thornton H E, Scaife A A, Hoskins B J and Brayshaw D J 2017 The relationship between wind power, electricity demand and winter weather patterns in GB Environ. Res. Lett. 12 064017
Treidl R, Birch E C and Sajeczi P 1981 Blocking action in the Northern Hemisphere: a climatological study Atmos. Ocean 19 37–41
Trigo R, Trigo F, DaCamara C C and Osborn T J 2004 Climate impact of the European winter blocking episodes from the NCEP/NCAR reanalyses Clim. Dyn. 23 17–28
You P, Vautard R, Naveau P and Cassou C 2007 Inconsistency between atmospheric dynamics and temperatures during the exceptional 2006/2007 fall/winter and recent warming in Europe Geophys. Res. Lett. 34 1–7