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Wind generation output during cold weather-driven electricity demand peaks in Ireland

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ABSTRACT

Recent cold winters and prolonged periods of low wind speeds have prompted concerns about the increasing penetration of wind generation in the Irish and other northern European power systems. On the combined Republic of Ireland and Northern Ireland system there was in excess of 1.5 GW of installed wind power in January 2010. As the penetration of these variable, non-dispatchable generators increases, power systems are becoming more sensitive to weather events on the supply side as well as on the demand side. In the temperate climate of Ireland, sensitivity of supply to weather is mainly due to wind variability while demand sensitivity is driven by space heating or cooling loads. The interplay of these two weather-driven effects is of particular concern if demand spikes driven by low temperatures coincide with periods of low winds. In December 2009 and January 2010 Ireland experienced a prolonged spell of unusually cold conditions. During much of this time, wind generation output was low due to low wind speeds. The impacts of this event are presented as a case study of the effects of weather extremes on power systems with high penetrations of variable renewable generation.

1. Introduction

The penetration of wind energy in the Irish power system has rapidly increased over the past decade (Fig. 1). There are two system operators on the island of Ireland: EirGrid in the Republic of Ireland, and SONI in Northern Ireland. As of January 2010, the total installed wind generation capacity in the Republic of Ireland stood at 1260 MW, compared to a total dispatchable capacity of 6317 MW which includes thermal, hydro and pumped hydro generation [1]. Installed wind capacity grew by 23% from 2008 to 2009 [2]. There is a further 273 MW of wind capacity in the Northern Ireland system, and a 2.4 GW total thermal capacity [3]. Over half of the thermal capacity on each system is from gas, with smaller contributions from coal, oil, and in the Republic, peat. The Republic's interconnection capacity with the smaller Northern Ireland transmission system is currently constrained to 200 MW for system security reasons [4]. In turn, Northern Ireland is interconnected to the British system via a 500 MW HVDC submarine link. Construction commenced in 2010 on a direct, 500 MW HVDC interconnector between the Republic of Ireland and Britain [5] and a proposed second interconnector between the Republic and Northern Ireland would reduce the present constraint on interconnection capacity. The government of the Republic has set a target of 40% of electricity generation to be from renewable sources by 2020 and it is likely that more than three quarters of this will come from wind, with most of the remainder coming from hydropower and biomass-fired thermal generation [6]. Since 2007, a single electricity market system operates throughout the entire island, whereby generators submit bid prices one day ahead of dispatch to SEMO, the Single Electricity Market Operator, which determines the lowest cost generation mix based on the submitted prices and forecasted demand [7]. Wind generation effectively receives priority dispatch by bidding a marginal price of zero. Compensation for wind generation is provided by means of a fixed feed-in tariff. Separate payments are made to generators for provision of capacity to the system.

Much has been written on the impacts of generation variability in power systems with high penetrations of renewable generators such as wind (e.g [5,8,9]). Peak electricity usage in temperate northwest European regions tends to occur during winter cold snaps, when demand is boosted by increased electric space heating loads. These cold snaps tend to coincide with periods of low winds. In 2006 an estimated 14% of residential electricity use in the

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Nomenclature

AIGS	All-island grid study
EV	electric vehicle
GW	gigawatt
HDD	heating degree-days
HVDC	high voltage direct current
MW	megawatt
SEMO	Single Electricity Market Operator
SMP	System Marginal Price
SONI	System Operator for Northern Ireland
TSO	Transmission System Operator

Republic of Ireland was for space heating and a further 23% for water heating [10].

In most continental climates, electricity demand exhibits a “U”-shaped response to ambient outdoor air temperatures, with demand increasing in summertime due to cooling and in wintertime due to heating loads. In a comparative study of Athens, Greece and London, UK, it was observed that, in London, demand tended to increase as air temperatures decreased and, unlike Athens, the summertime demand for cooling did not have a significant effect [11]. The demand/temperature response in Ireland is likely to be similar to that of London, due to the similarity in climate. In the southern USA, both total electrical energy demand and the shape of the daily load profile have been noted to be sensitive to extremes of cold, with the severity, rather than the duration, of the cold snap being the dominant factor [12]. Sinden [13] used meteorological data from surface stations to examine the long-term correlation of wind power availability and electricity demand in the UK. Others have used surface wind speed data driven simplified models of wind energy production in order to investigate the variability of wind power during the wintertime peak month of UK electricity demand (e.g [14]).

The climate of Ireland is generally mild due to the strong marine influence. Prolonged spells of extreme heat or cold are rare, and the mean December air temperature in Dublin is 6 °C [15]. The first week of December 2009 was mild and windy, but a high pressure system dominated the weather for the remainder of the month, bringing northerly airflows and cold temperatures (Fig. 2). The month of December was the coldest in 28 years in many parts of the country, the cold spell of winter 2009/10 having been compared to previous cold periods which occurred in 1947, 1962/63, 1979 and 1981/82 [16]. Air temperatures remained below the long-term average for the time of year from 16th December to 9th January (Fig. 3).

Lamb [17] devised a categorisation system for the most prevalent large-scale atmospheric circulation patterns or “airflows” over Britain and Ireland. General weather characteristics can then be assigned to each airflow type. The dominant large-scale airflow pattern during the period of interest (Fig. 4) most closely resembles the “northerly” circulation pattern in Lamb’s categorisation [18].

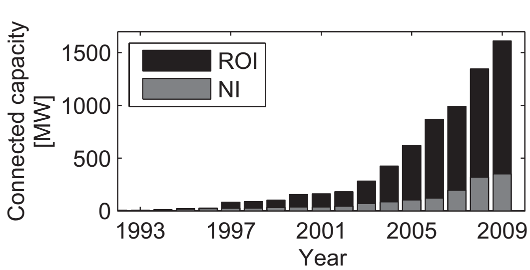

Fig. 1. Installed wind generation capacity in the Republic of Ireland (ROI) and Northern Ireland (NI), 1992–2009. ROI figures are to December 2009, NI figures are to August 2009.

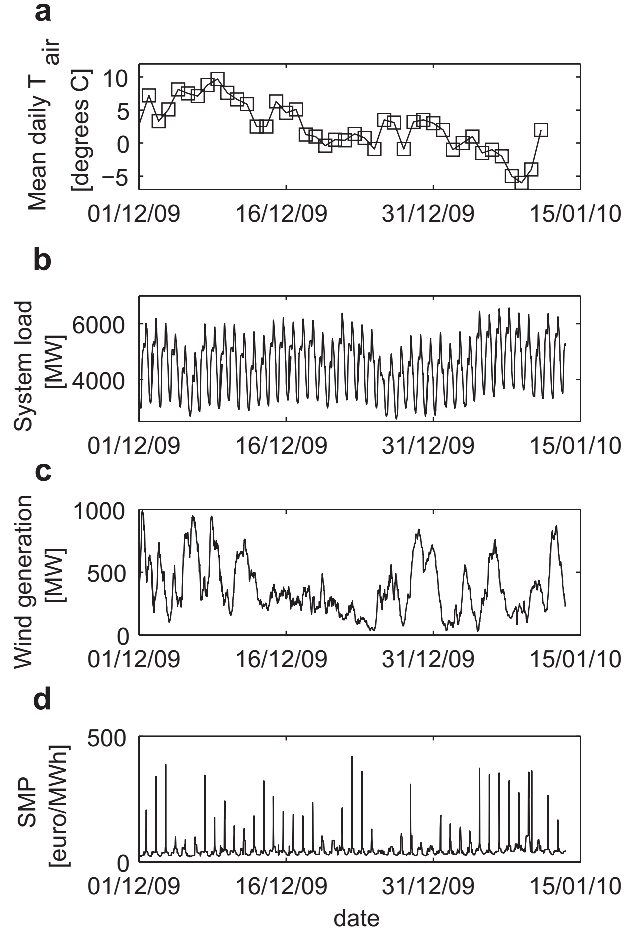

Fig. 2. (a) Daily mean air temperatures from four stations; (b) total system load; (c) total system wind generation output; (d) market price for the study period.

Several areas of low pressure lie over continental Europe and the North Sea. An area of high pressure is present to the northwest. This airflow pattern brings northerly winds and low temperatures to Ireland and Britain and is relatively infrequent, particularly in winter, where it occurs 3.6% of the time [18]. It has been noted that the interannual variability of European wind speeds, particularly in

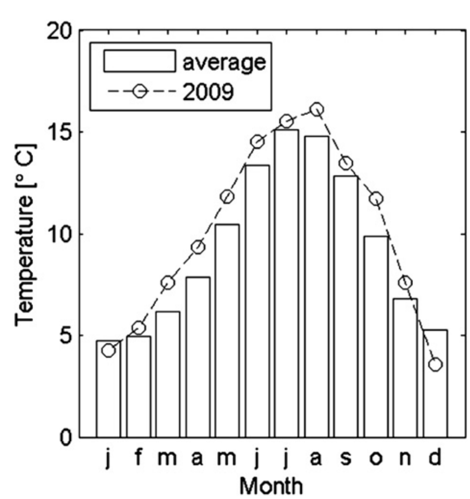

Fig. 3. Plot of long-term average air temperature and air temperature from over the study period.

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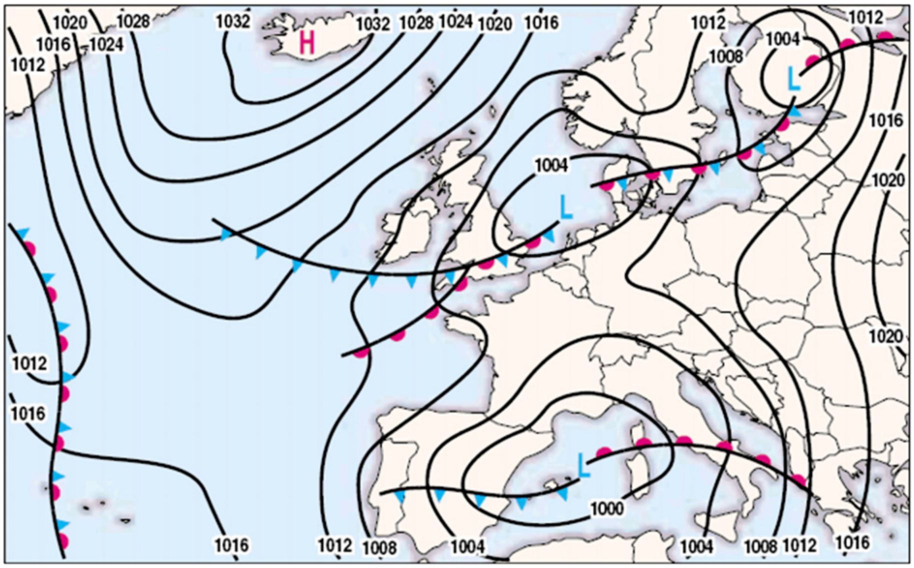

Fig. 4. Meteorological situation on 5th January 2010 showing high pressure over Iceland, low pressure over the North Sea and northeasterly airflows over Ireland. Chart reproduced by permission of accuweather.com.

the Baltics, is dependent on variations in the large-scale North Atlantic circulation [19].

Thus, the Irish system is interesting for several reasons: it is weakly interconnected to neighbouring systems; it already has a significant wind generation capacity and this is projected to grow rapidly in the years to 2020; and finally, as it covers a relatively small area, fast-moving large weather systems can quickly alter wind and temperature conditions throughout the entire island. From the point of view of energy supply and demand, the prolonged cold spell of 2009/10 is interesting because it is the most severe such event to occur in Ireland in the era of widespread, large-scale wind generation of electricity. Although mean wind speeds for early December were close to the long-term average, winds were below the average for the time of year during most of the cold period, particularly from the 19th to 30th of December. This paper will examine the relationship of electricity demand to air temperature during this period, and will test the hypothesis that the concurrence of low winds and extremes of cold leads to large spikes in electricity demand from non-wind generators, thus threatening system security. Weather effects on the variability of supply other than the variability of wind generation (such as failures in the transmission system due to extreme weather events) are not considered here.

2. Data & methods

Daily minimum, mean and maximum air temperatures were obtained from the European Climate Assessment dataset [20]. Three stations from different parts of the country, with good data coverage, were chosen: Dublin (Phoenix Park), close to the east coast of the country; Malin Head in the northwest; and Birr in the central midlands. The Dublin measurement station is in the most densely populated and heavily industrialised region of the country and is therefore close to a large proportion of the country's domestic and industrial electricity demand. Temperature records were available from 1881 to June 2010.

As an indication of climate-driven electricity demand, heating degree-days (HDD) were calculated using the Dublin air temperatures, using the formulation of [21], with a base temperature, T_b, of 15.5 °C:

$$\begin{aligned} HDD &= T_b - \frac{1}{2}(T_{\max} - T_{\min}) && [T_{\max} \leq T_b] \\ HDD &= \frac{1}{2}(T_b - T_{\min}) - \frac{1}{4}(T_{\max} - T_b) && [T_{mean} \leq T_b < T_{\max}] \\ HDD &= \frac{1}{4}(T_b - T_{\min}) && [T_{\min} \leq T_b T_{mean}] \\ HDD &= 0 && [T_b < T_{\min}] \end{aligned} \quad (1)$$

where, $T_{\min}$, $T_{\max}$, T_{mean} are daily minimum, mean and maximum temperatures, respectively. Application of Eq. (1) produced a series of daily HDD values which were then totalled on a monthly basis for each year of available temperature data.

Half-hourly figures for total system demand (on the combined Ireland and Northern Ireland systems), total wind generation and the system marginal price (SMP) paid to generators were obtained from SEMO. The SMP is initially calculated one day ahead of dispatch from the lowest cost combination of generator offers which can satisfy forecasted demand, and includes the actual cost of generation as well as startup and no-load costs. As the amount of installed wind generation has grown so rapidly, particularly during 2009, the time series of wind generation used in this study is normalised to installed wind capacity over time. The Pearson product-moment correlation coefficient, R, was calculated to assess the relationship between daily total electricity demand (D) and daily mean air temperatures (T_a) at all measurement locations:

$$R = \frac{\mathrm{cov}(D, T_a)}{\sigma_D \sigma_{T_a}} \quad (2)$$

where, cov denotes the covariance of two variables and σ denotes standard deviation. All calculations were carried out using the Matlab computing environment and functions from the Matlab statistical toolbox, including corrcoef() to calculate R and robustfit() to calculate linear regression coefficients.

3. Results

3.1. Supply and demand: general responsiveness to climate

Weak negative correlations were observed ($-0.22 < R < -0.16$) between normalised daily wind generation on the whole system and air temperatures over the study period of December 12th-January

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12th for all years 2006–2009 (Fig. 5a & Table 1). Although the negative correlation is weak at all locations, it is slightly stronger (−0.22) for Malin temperatures than for those recorded at Dublin (−0.16), which is expected due to the concentration of wind generation in the west of the country. Daily total system demand shows a decrease as daily mean air temperature increases, reflecting the contribution of space heating to electricity demand (Fig. 5b and Table 1). The choice of measurement location for air temperature has little effect on the result ($-0.65 < R < -0.62$), due to the small climatic variations within Ireland (cf. Table 1). The correlation coefficient between daily total demand and air temperature at Dublin was −0.63, and the daily demand sensitivity to air temperature was −1.6 GWh per °C.

3.2. *Winter 2009/2010 demand and wind generation*

December 2009 had a heating degree-days figure of 360.3. The long-term average (1880–2009) is 311.0, with a standard deviation of 48.2, while the figure for December 2008 was 331.1 degree-days. Fig. 6 shows that the diurnally averaged system demand during late December 2009 and early January 2010 was virtually unchanged from that of a year earlier. Average hourly wind generation has increased by almost 50 MW during this time. The capacity factor for wind generation on the all-island system over the period 12th December 2009 to 12th-January 2010 was approximately 20%, much lower than the same period in earlier years: 39% capacity factor for 12th December 2006-12th January 2007, 43% for 12th December 2007-12th January 2008 and 33% for 12th December 2008-12th January 2009.

Maximum daily prices on the electricity market throughout the period 19th to 30th December were comparable to those of early December, when wind generation was often higher (Fig. 2). Reductions in demand in late December due to the holiday season, and year-on-year compared to 2008 due to the economic recession, and the presence of sufficient dispatchable generation capacity on the system are likely to be the factors behind this.

4. Discussion

Daily total wintertime electricity demand in Ireland has been shown to increase by around 1.6 GWh with every 1°C drop in air temperature. December of 2009 was the coldest December in almost three decades in many parts of the country and the potential demand for space heating, as indicated by heating degree-days indicator, was 16% higher than the long-term average for the month. However, the economic recession in Ireland resulted in reduced electricity demand in 2009 when compared to 2008 [1]. The percentage year-on-year decline was smaller between December 2009 and December 2008 (2%) than for previous months

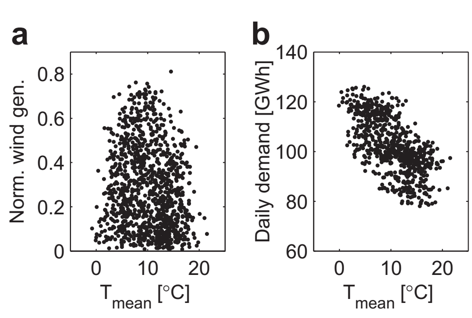

Fig. 5. (a) Normalised daily wind generation on the whole system and air temperatures over the study period for all years 2006–2009; (b) Daily total system demand shows a decrease as daily mean air temperature increases, reflecting the contribution of space heating to electricity demand.

Table 1
Influence of choice of air temperature measurement station on correlation results between temperature and total wind generation; correlation of temperature and wind generation; sensitivity of total system demand to temperature.

Measurement location	Dublin	Malin	Birr
Correlation of wind generation & air temperature	−0.16	−0.22	−0.18
Correlation of total demand & air temperature	−0.63	−0.62	−0.65
Sensitivity of total daily demand to temperature [GWh/°C]	−1.6	−1.9	−1.6

(7.5% between October 2009 and October 2008 and 6% between November 2009 and November 2008) and this reduction in the decline was likely due to increased demand for electric heating during the cold spell. The winter demand forecasts issued in August 2009 by the Republic's TSO showed an expected reduction in weekly peak demand of up to approximately 400 MW during the holiday season of late December, compared to the first half of December [4]. The reduced industrial activity during the holiday period is very likely to have mitigated the additional demand due to the cold conditions. Larger peaks in daily demand and SMP were observed in the week commencing Monday 4th January, by which time most industrial activity had resumed, and temperatures still remained well below the average for the time of year. The transmission system operator and distribution system operator for Ireland run separate demand side management schemes designed specifically to reduce peak winter demands. Of these, the TSO's scheme, usually accounting for up to 150 MW of demand reduction, does not run on the week of December 25th [22]. The daytime demand peaks of the 4th, 6th and 7th of January on the Republic of Ireland system were particularly high, and exceeded the maximum forecasted winter peak values by several hundred MW [4].

Although the combination of low air temperatures with resulting increased demand for space heating and low generation from wind did not appear to have any adverse effects on system operations or wholesale electricity pricing in the market in this particular case, there remains a strong case for detailed consideration of unusual meteorological events in future generation portfolio modelling studies, where the performance of different generation mixes is ascertained (e.g [23,24].), particularly in portfolios with high wind penetration. The capacity credit for wind is likely to be sensitive to the frequency and duration of such extreme weather events. Portfolio five of the 2020 electricity system, identified in the All-island Grid Study (AIGS), has a total generation capacity of 14 200 MW, including 6000 MW of wind, to satisfy a minimum demand of 3500 MW and a peak demand of 9600 MW, while exceeding the 40% renewable generation target [23]. It is clear from these figures that if peak demand coincides with a period of widespread, extremely low winds, then there will be insufficient capacity on the system and measures such as interconnection, storage or demand side management will be required, and the portfolio does include 1000 MW of interconnection to Britain [23]. The meteorological situation of December 2009 is atypical and may be under-represented in the wind datasets (which are derived from wind maps primarily intended for wind resource assessment) underlying the AIGS simulations.

In addition the Republic of Ireland has a target of generating 10% of transportation energy requirements from renewable sources by 2020 [23]. The requirement will be partially met by electric vehicles (EV's) powered by renewable sources [6]. Northern Ireland has set a renewable target of 12% of electricity production from indigenous sources by 2012. A revised target of 42% power from renewable sources by 2020, mostly from offshore wind power, is currently under consultation [25]. A snapshot of wind power analyses for EV charging is presented in Fig. 7 and shows that the mean wind

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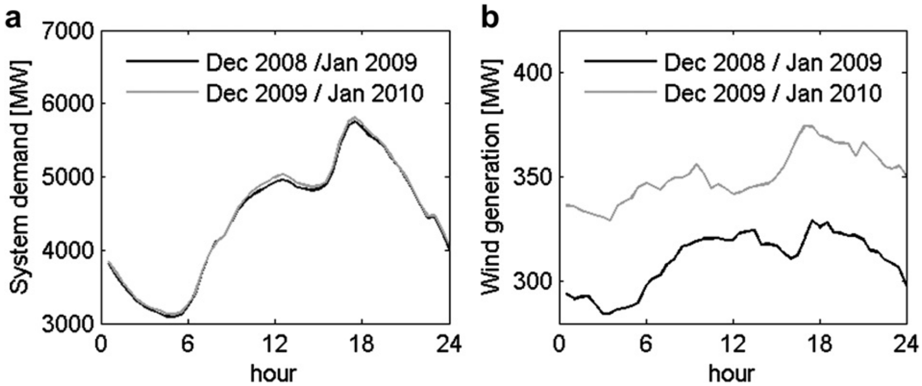

Fig. 6. Daily average profiles of (a) system demand and (b) wind generation from the study period in and 2010.

output is much higher in winter, but with a high variability including sharp sudden cold snaps with no or very low wind. This is typical of annual wind power generation in Ireland and the UK. The night-time valleys can be seen as potential opportunities for grid-connected EV's to act as storage, but with low mean wind output in summer and high variability in winter the potential for consistent use of EV-based storage looks limited, even with increased wind generation on the system in future [26]. Furthermore, usage patterns also vary during week days, at weekends and between different seasons depending on school, sporting and holiday activities, as well as weather conditions. The issue of EV 'anxiety charging' may add to the uncertainty in demand during extreme weather events. Varying the charge rate and number of hours of charging for the various numbers of EV's over the day could result an instantaneous uncontrolled load of anything from 200 MW up to 600 MW on the grid in Ireland [27].

A further impact of extreme cold weather that has not received adequate attention in studies in Ireland to date is the impact of increasing variable wind power on the gas network. Increasing levels of varying wind power will have the effect of changing the usage profile of gas at thermal generators as wind ramps up and down on the system. This may be amplified during extreme weather events, particularly long unexpected cold periods. Ireland imports approximately 94% of its natural gas supply from Great Britain via the Moffat entry point and the remainder comes from the Kinsale gas field [28]. The Joint Gas Capacity Statement also acknowledges that the low levels of wind power and extreme periods of cold weather such as that experienced during the winter of 2009 placed significant demands on the gas systems in Ireland and that there will continue to be a substantial demand on gas generation to back-up wind power [28]. Qadrdan et al. [29] note that wind integration studies in Great Britain have also neglected the impacts on the gas network and that large wind power penetration will cause increased flows and compressor power consumption on the gas network, whereas during low wind periods linepack depletion can limit the ability of the gas network to supply gas thermal generators. Perhaps Ireland's higher expected levels of installed wind power may lead to effects on the gas network similar to those identified by Qadrdan et al. [29], who demonstrated that gas suppliers, shippers and generators will be exposed to hourly balancing costs, affecting gas prices and procurement. Such impacts could also be amplified during an unexpected period of extreme cold.

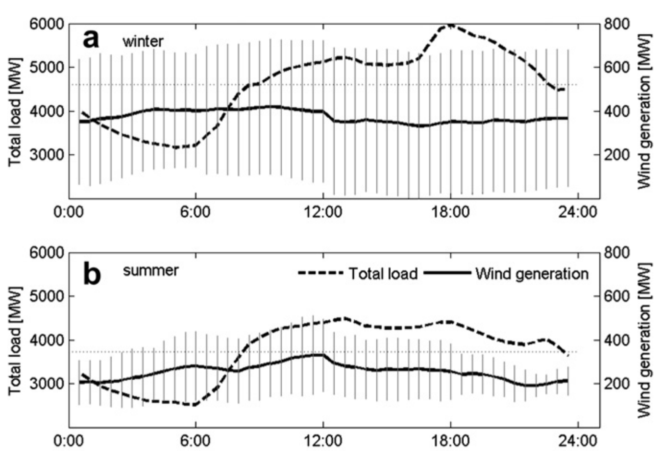

Fig. 7. Typical winter and summer half hourly means of total system load and wind generation on the all-island grid for: (a) the fortnight beginning 23rd January 2009; and (b) the fortnight beginning 5th June 2009. Vertical bars illustrate the hourly variability ($\pm\sigma$) about the mean of wind generation over the respective periods. The horizontal dotted lines represent the mean system load over the respective periods.

5. Conclusion

Despite the demonstrated sensitivity of electricity demand in Ireland to low temperatures, a prolonged cold spell overlapping with a shorter period of low wind generation in Ireland did not have a severe impact on either system security or electricity market prices. This can be partially attributed to the fortuitous timing of the cold snap, which mainly coincided with a period of reduced industrial electricity demand due to the holiday season, and the year-on-year decline in demand due to the effects of the economic recession in Ireland. Upon the resumption of normal industrial activity in early January, record daytime demand peaks of up to 4950 MW were encountered on the Republic of Ireland system. Although it would appear reasonable to expect a relationship between air temperature and total wind generation, due to the common underlying meteorological influence of Lamb's large-scale airflow types, only a weak negative correlation was evident between the two quantities.

Further work is necessary in order to fully evaluate the combined potential impacts of prolonged cold snaps and periods of low winds under future projected generation scenarios, which will become more reliant on wind as penetration increases. We envisage that this will be achieved by frequency analysis of the meteorological records of wind speeds and air temperatures, seeking to quantify, independently and jointly, return periods for prolonged periods of low wind speeds and low temperatures. The use of more sophisticated techniques such as mutual information analysis should also lead to a clearer understanding of the inter-relation of these factors. This analysis will be carried out by the authors in conjunction with studies of the impacts of variable wind generation on the gas network and the effects on the power system of increased demand from EV charging.

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