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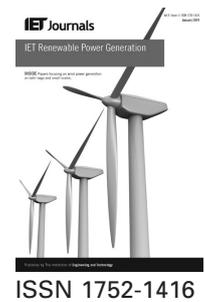
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Going with the wind: temporal characteristics of potential wind curtailment in Ireland in 2020 and opportunities for demand response

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Abstract: The Republic of Ireland and Northern Ireland have ambitious targets for 40% of electricity to be supplied by renewables by 2020, with the majority expected to be supplied by wind power. There is, however, already a significant amount of wind power being turned down, or ‘curtailed’, and this is expected to grow as wind penetrations increase. A model-based approach is taken to estimate curtailment using high-resolution wind speed and demand data covering four years, with a particular focus on the temporal characteristics of curtailment and factors that affect it. The model is validated using actual wind output and curtailment data from 2011. The results for 2020 are consistent with previously published estimates, and indicate curtailment levels ranging from 5.6 to 8.5% depending on assumptions examined in this study. Curtailment is found to occur predominantly at night, and to exhibit stochastic variability related to wind output. To accommodate high penetrations of wind power, the findings highlight the value of flexible demand over relatively long time-periods. The model’s output data have been made publicly available for free for further investigation.

1 Introduction

1.1 Integrating high penetrations of wind power

With anticipated large penetrations of wind power, there is increasing concern about periods when there is too much wind power and not enough demand on the system. During such periods wind power can need to be turned down, also referred to as ‘dispatched down’. Dispatch down can be required at the system level, for example, to maintain system stability, in which case it is referred to as ‘curtailment’, or it can be required locally, for example, to relieve local network congestion, in which case it is referred to as a ‘constraint’ on wind output.

Minimising or avoiding dispatch down improves the utilisation of wind energy, and as such can contribute towards decarbonisation goals. Methods to reduce dispatch down have been investigated as part of past studies concerned with integrating high penetrations of renewable energy onto the grid. Delucchi and Jacobson [1], in their evaluation of the feasibility of providing all energy for all purposes globally, suggest methods for dealing with high penetrations of intermittent renewables, including wind: creating diversity by geographically dispersing generators; using large-scale energy storage, either centralised, for example, hydro-electric facilities, or distributed, such as fleets of electric vehicles; hydrogen production during periods of excess generation; and demand response in the form of flexible heating and cooling demands.

Elliston *et al.* [2] found that it is technically feasible for 100% of electricity demand in the Australian New Energy Market to be met by renewable electricity, including 30% met by wind power. In their simulations, pumped hydro power was used to opportunistically charge during periods of excess renewable power. In a similar study, Budischak *et al.* [3] modelled combinations of wind, solar and electrochemical storage (batteries, and fuel cells) that could provide power for 90–99.9% of hours for the North American PJM grid. Looking at the pan-European grid, Rasmussen *et al.* [4] quantify the storage requirements for achieving a highly renewable powered European power system, and found this could be achieved with a combination of a relatively small, high-efficiency and short-term (6 h) storage, such as pumped hydro, and a larger, less efficient and long-term (seasonal) storage, such as hydrogen storage.

1.2 Wind power curtailment in Ireland

Although the studies above are concerned with methods for integrating wind in future scenarios, there are nonetheless present-day concerns with wind integration in the Republic of Ireland and Northern Ireland, where there is already a considerable amount of wind energy being dispatched down. In 2011, for example, 119 GWh of wind energy was dispatched down, equivalent to 2.2% of the total available wind output [5]. An estimated 80% of dispatch down in

2011 was due to curtailment, with the remaining 20% associated with constraints.

Although there are separate transmission system operators in the Republic of Ireland and Northern Ireland (Eirgrid and SONI, respectively), the two systems are interconnected and operate under a single electricity market. For the purposes of this paper, therefore, these will be referred to as a single ‘All-island’ power system [6].

The All-island system has ambitious targets for 40% of electricity to be generated from renewables by 2020 [7, 8]. With one of the most abundant wind resources in Europe [9], it is expected that in 2020 wind power will account for almost 93% of renewable electricity. Thus 37% of electricity demand is expected to be met by 5 GW of wind capacity. For comparison, in 2012 2.1 GW of wind power had been installed [6].

The All-island system is relatively small, islanded and has low levels of interconnection with neighbouring power systems. Owing to the expected growth in wind power, dispatch down because of curtailment could increase considerably. Constraints on wind output are expected to be minimised in future because of on-going network reinforcements [10]. There is, therefore, an interest in estimating the level of curtailment of wind power in the future [11], as well as in investigating measures to reduce curtailment.

1.3 Estimates of wind curtailment in 2020

An early attempt at estimating curtailment came from the ‘All Island Grid Study’, which consisted of several technical reports commissioned by government to investigate generation portfolios for achieving 2020 renewables targets. As part of the study, Doherty estimated that curtailment would be negligible on the All-island system in 2020 for wind power penetrations below 5 GW, with curtailment rising to 14.4% of available wind energy with 9 GW of wind power [12]. Curtailment is estimated in the report using a system non-synchronous penetration (SNSP) limit of 66.6%. The SNSP is calculated as [13]

$$\text{SNSP} = \frac{\text{wind generation} + \text{HVDC imports}}{\text{system demand} + \text{HVDC exports}} \quad (1)$$

Note there is a difference between (a) the instantaneous SNSP which will vary through time depending on the instantaneous levels of wind generation, demand and HVDC imports and exports, and (b) the SNSP ‘limit’, which refers to the threshold above which the instantaneous SNSP cannot be allowed in order to preserve system stability.

Where HVDC stands for high-voltage direct current power flows across the Ireland-GB interconnectors (see Section 2.4). As part of the same study, Meibom uses a mixed integer, stochastic, unit commitment and dispatch optimisation model to analyse the impact of increased wind penetrations [14]. No curtailment of wind power was found up to installed wind capacities of 6 GW.

Touhy and O’Malley [15] extended the model used in the All Island Grid Study to include the use of pumped storage as a measure to reduce curtailment and increase capacity factors for conventional fossil-fuel generators. Wind capacities ranging between 3 and 15 GW were considered, and system security limits were modelled by assuming a minimum of eight large generators were required on the system at all times. The results indicated that curtailment

was negligible below installed wind capacities of 7 GW, and that while storage reduced curtailment levels, it was not economically viable for the wind penetrations that were considered.

Denny *et al.* [16] also extended the All Island Grid Study in order to consider the impact of increased interconnectors on the integration of high penetrations of wind power on the All-island power system, including the effect on curtailment. Curtailment was found to be negligible with installed wind capacity of 6 GW, and a doubling of interconnection with GB from 1 to 2 GW was found to reduce curtailment from 0.15 to 0.12%.

All of the above studies therefore found curtailment not to be an issue for the penetrations of wind power that can be expected in 2020. They all, however, used pre-recession growth estimates for demand, and since they were published these levels of demand are no longer correct. For example, Tuohy and O’Malley used a peak demand of 9.6 GW, and annual demand of 54 TWh, while current projections are for 7.3 GW of peak demand and 40 TWh for annual demand [6]. For comparison, peak demand in 2012 was 6.5 GW. As curtailment is dependent on the demand as well as the wind output, there is a need to revisit curtailment estimates given realistic estimates of demand growth.

Given the revised, post-recession demand growth estimates, McGarrigle *et al.* [11] estimate wind curtailment on the All-island power system, with the aim of determining required penetration levels to meet 40% renewable energy targets. A mixed integer programming, unit commitment and economic dispatch model is used, which included estimations for offshore wind output, and a simplified model of the GB power system. System security limits were included in the model based on published Transmission Constraint Group rules. Their results show that a SNSP limit of 60% resulted in curtailment levels of 14%, reducing to 7% for a SNSP limit of 75%. Owing to the use of revised demand growth estimates, this study indicates that curtailment is likely to be considerable on the All-island system.

1.4 Demand response to aid the integration of wind power

The studies described above have considered various measures to reduce curtailment including storage, interconnectors and the relaxation of system security limits. Demand response is an alternative measure which is considered here. Demand response refers to consumers time-shifting electricity consumption in response to a signal, usually in the form of a financial incentive [17].

Keane *et al.* [18] investigated the use of demand response as a resource for the flexible operation of the All-island power system with high penetrations of wind power. A demand model was developed that characterises demand response resources as units that could be integrated into existing unit commitment models. They conclude that demand response can improve the reliability and efficiency of the system by reducing the use of conventional fossil fuel plant, although the impact on curtailment is not considered. Their study illustrates the potential importance of demand response on the All-island system. The focus of the study was, however, on the use of demand response for reducing peak demand, while this paper focuses on the potential for demand response to reduce curtailment by increasing demand during periods of excess wind generation.

The aim of this paper therefore is to investigate the potential for demand response to reduce curtailment on the All-island system. The next section describes the model that was developed to characterise the temporal characteristics that can be expected of curtailment in 2020. The model also provides estimates of total annual curtailment which can be compared to previous work.

2 Model overview

Fig. 1 shows the high-level architecture of the model, which can be seen to consist of two main components: a wind power model and a curtailment model. The methodology for the model is based on the operating requirements faced by the system operator (as described in Section 2.3). The model does not account for unit commitment and economic dispatch of generators as (a) the paper is not concerned with the precise plant mix providing synchronous generation, so long and sufficient capacity is available, and (b) wind generation has the lowest short term marginal running costs of all major generators on the system and it is, therefore assumed that wind will be dispatched as much as possible within the constraints of the curtailments rules. The model was implemented in Matlab.

The wind power model takes an input that includes hourly wind speed data across a geographic grid, and produces aggregated hourly wind output for the whole island. The curtailment model takes as input the hourly wind output, hourly demand data and a set of curtailment rules to produce hourly estimates of curtailment. The temporal characteristics of the curtailment can then be analysed, and totals compared to previous work. The following sections

describe the components of the model and data used in more detail.

2.1 Wind power model

To provide good temporal representation of curtailment, particular attention was given to developing an accurate estimation of the temporal variability of wind power on the All-island system. Similar to the approach taken in [19], high-resolution (half-hourly or hourly) historical wind speed data is used covering a period of several years. Owing to the use of multiple years of data, the model accounts for the distribution of wind speed over multiple years, and produces results that illustrate the possible range of future curtailment, rather than an estimate for a single year. This is a source of novelty compared with previous studies.

In addition to the requirement for several years of data, a good geographic spread was also needed to combine with the known geographic distribution of installed wind capacity in Ireland. Hourly wind speed data at 10 m for 2009 and 2010 was therefore sourced from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CSFR) product [20] covering the island of Ireland at 0.5° horizontal resolution, resulting in 51 grid nodes. For more recent data covering 2011 and 2012, the NCEP Climate Forecast System Version 2 (CSFV2) was used, which uses an identical model to CSFR, and can be considered a seamless extension to it.

Fig. 1 shows how the hourly gridded wind speed data is used to calculate estimates of hourly gridded wind output. Wind speeds at 10 m are scaled up to a hub height of 80 m

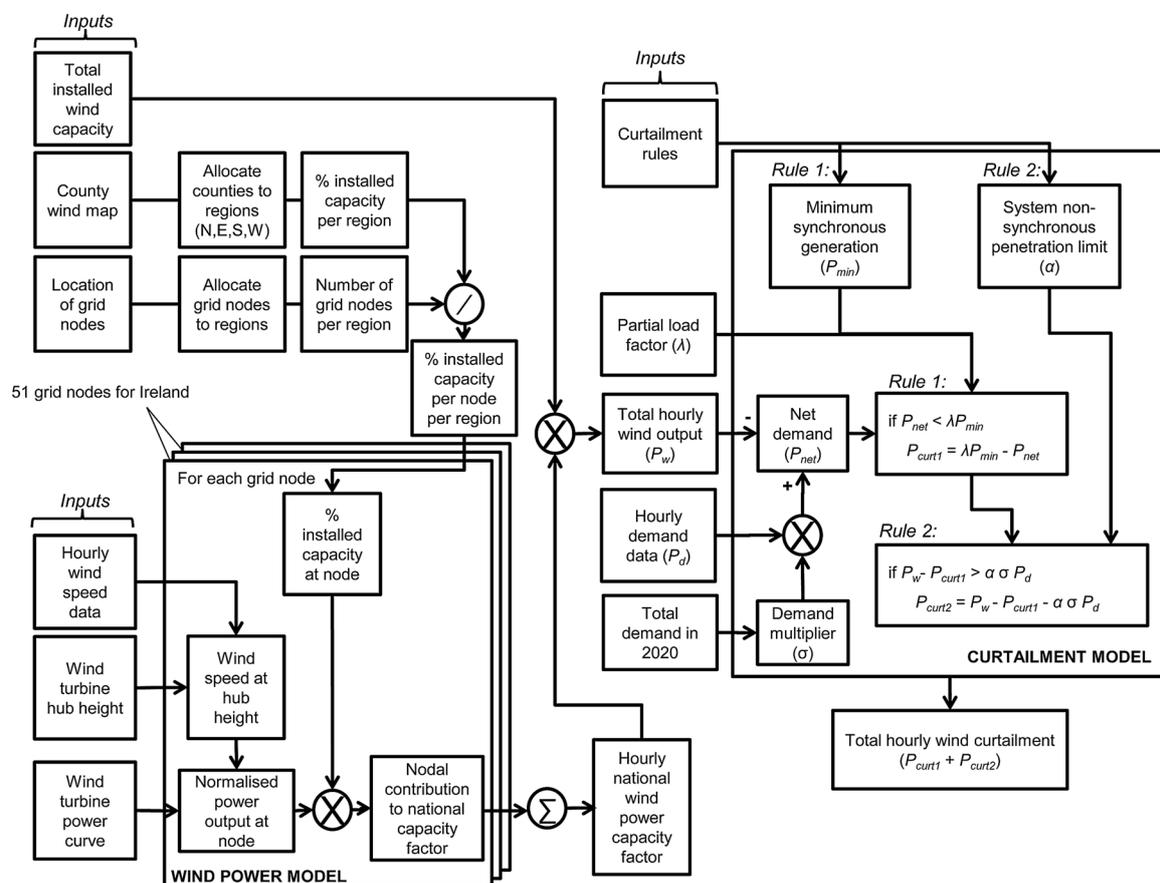


Fig. 1 Model architecture for estimation of wind power and curtailment

using the power law method as

$$u_{80} = u_{10} \left(\frac{80 \text{ m}}{10 \text{ m}} \right)^p \quad (2)$$

where u_x is the wind speed at height x . The p value depends on surface roughness and a value of 1/7 was used, as in [19, 21]. The authors note that while the power law method for extrapolating wind speed is common, it has been shown to underestimate wind speeds at 80 m by an average of 1.3 m/s compared to a method that calculates vertical wind profiles based on a least-squares fit to twice-a-day wind profiles from sounding data [22]. Within the context of this paper, however, where the focus is on the temporal characteristics of the wind output, the use of the power law method is not inappropriate and, as will be demonstrated later, produces results that are validated against measured data.

Having calculated wind speeds at hub heights across the geographic area, a normalised wind output for each grid node ($P_{\text{node, norm}}$) is calculated based on the wind speed and a power curve based on the power curves of three commercially available large wind turbines. Note the model therefore assumes that all the wind turbines installed on the island are identical. This power curve is described in [23], and used in [24–26]. Turbine power output (P) and normalised wind output for each grid node ($P_{\text{node, norm}}$) are calculated as (see (3))

$$P_{\text{node, norm}} = \frac{P}{1000} \quad (4)$$

The normalised wind output for each grid node is converted to a nodal contribution to the (hourly) national wind capacity factor by multiplying it by the percentage of the total installed wind capacity that is allocated to the node (N_{node}). This is calculated as follows. The Irish County Wind Map provides installed capacities for each county [27]. The island is then divided into four regions (North, East, South and West), each county is assigned to one region, allowing percentages of total installed capacity to be calculated for each region (N_{region}). The number of grid nodes in each region is counted (n_{region}), allowing N_{node} to be calculated as

$$N_{\text{node}} = \frac{N_{\text{region}}}{n_{\text{region}}} \quad (5)$$

Note the model therefore assumes that within each region the wind turbines are evenly distributed between the region's grid nodes. Each nodes contribution to the national hourly capacity factor (C_{node}) is then calculated as

$$C_{\text{node}} = N_{\text{node}} \times P_{\text{node, norm}} \quad (6)$$

and the national hourly capacity factor (C_{national}) is calculated

as the sum of the individual nodal contributions

$$C_{\text{national}} = \sum_{\text{node}} C_{\text{node}} \quad (7)$$

Finally, the national total hourly wind output (P_w) is calculated from the national capacity factor and total installed wind capacity (N_{national}) as

$$P_w = C_{\text{national}} \times N_{\text{national}} \quad (8)$$

For 2020, the regional distribution is assumed unchanged, and projected total installed wind capacity for the All-island system is taken to be 5061 MW [6]. The model does not account for offshore wind power, as only 0.2 GW is expected to be installed by 2020 [6].

2.2 Demand data

Owing to the inherent time-correlation between wind and demand, concurrent demand data was required to estimate curtailment. Historic half-hourly demand data for 2009 through to 2012 was obtained from the Irish Single Electricity Market Operator (SEMO). This was then converted to hourly values and adjusted to account for day-light saving. Similar to the process adopted for wind, demand data is scaled up according to 2020 growth estimates [6]. Historic demand data is, therefore uniformly increased by 17% for 2020 estimates, as consistent with [11].

Note that the demand data is the total system demand and therefore includes demand that has to be met because of transmission and distribution losses. Losses are therefore accounted for implicitly in the model through the use of this data and are assumed to be unchanged compared to the historic data. Where demand is scaled up to 2020 levels, losses are therefore also assumed to scale proportionally.

2.3 Curtailment model

The curtailment model is an implementation of curtailment rules taken from the 'Transmission Constraint Groups' and 'Operating Security Standards' documents [28], which detail the rules that govern which conventional generators need to be kept on-line for system security reasons. There are five system security limits described which necessitate curtailment [5]:

- system stability requirements,
- voltage control requirements,
- the SNSP limit,
- operating reserve requirements and
- morning load rise requirements.

The first two requirements (system stability and voltage requirements) have been implemented in the model using one rule. The Transmission Constraint Groups document gives the combinations of generators that can satisfy the two requirements, and the process adopted was to select the combination of generators that could satisfy all the

$$P = \begin{cases} 0 & \text{when } u_{80} < 3 \\ 0.0015u_{80}^5 - 0.1967u_{80}^4 + 4.0058u_{80}^3 - 19.268u_{80}^2 + 43.607u_{80} - 50 & \text{when } 3 \leq u_{80} \leq 13 \\ 1000 & \text{when } 13 \leq u_{80} \leq 25 \\ 0 & \text{when } u_{80} > 25 \end{cases} \quad (3)$$

requirements with lowest combined rated capacity. As in [11], the Transmission Constraint Groups are assumed unchanged out to 2020, because of uncertainty about which might be relaxed or changed. This results in three ‘minimum synchronous generation’ limits of 2503, 2258 and 2416 MW for week daytime, weekend daytime and night-time, respectively. These values, however, do not account for the fact that generators can be run at part load and so these limits are multiplied by a ‘partial load factor’ of 50%. In the model, wind power is curtailed if net demand falls below the minimum synchronous generation limits, as shown in Fig. 1 by the ‘Rule 1’ boxes.

The third requirement, SNSP limit, is implemented by its own curtailment rule. The model simulates three SNSP limits: the present limit of 50%, and two potential future limits of 60 and 75%, which are reported to become technically feasible in 2020 [13]. In the model, wind power is therefore further curtailed if the remaining wind power is greater than the demand multiplied by the SNSP limit as shown in the ‘Rule 2’ boxes in Fig. 1.

The final two requirements are not separately accounted for in the model. It should be noted therefore that the model may under-estimate curtailment, particularly during morning periods when demand ramp up which may require additional reserve capacity.

In the model, the two curtailment rules are modelled as ‘hard’ limits, which cannot be violated. The alternative use of ‘soft’ limits, which can be violated but which might impose a price penalty, was applied by McGarrigle *et al.* [11] and resulted in negligible differences in curtailment levels.

2.4 Interconnection with the GB power system

Interconnectors can affect curtailment by allowing the All-island system to export to GB during periods of excess wind generation, as investigated by the authors [11, 16]. Including interconnectors within the model is useful therefore as it allows the results to be compared with estimates from previously published studies.

The All-island system is interconnected with the GB power system via two interconnectors: the Moyle interconnector between Northern Ireland and Scotland, and the East-West interconnector between Ireland and Wales, both of which are rated at 500 MW in both directions. The number of interconnectors is expected to remain unchanged in 2020 [11], resulting in a potential 1 GW of export available to GB for the purposes of reducing curtailment.

It is not always possible, however, to predict whether export capacity will be available [6], as periods of excess wind generation on the All-island system are likely to coincide with periods of excess wind generation on the GB system. Furthermore, it should be noted that the Moyle interconnector has historically suffered from technical faults that limit its capacity [6]. The approach taken in the model was therefore to assume 500 MW of exports were constantly available to avoid curtailment.

3 Model outputs and validation against historic data

3.1 Output of the model over an illustrative week

Fig. 2 shows the output of the model over an illustrative week using data from January 2009. Demand and wind power are shown in Fig. 2a and have been scaled up to 2020 levels.

The week is characterised by generally high wind output apart from a calm during the middle of the week. Fig. 2b shows the resulting net demand and the two curtailment variables which correspond to the model’s two curtailment rules as described in Section 2.3. The first curtailment rule is associated with the minimum synchronous generation limits, which are shown by the grey line on the figure labelled as ‘TCG’ (Transmission Constraint Group). If net demand falls below this limit, then wind is curtailed, and the resulting total curtailment associated with this rule is illustrated in Fig. 2c. Note that the use of interconnectors has not been included in these illustrations.

The second curtailment rule is associated with the SNSP limit, which is taken to be 60% in this example. If the net demand after curtailment because of the first rule is below the demand multiplied by the SNSP limit, then wind is curtailed further. The resulting total curtailment because of this second rule is shown in Fig. 2c as the black area.

Fig. 2d provides an alternative visualisation of the total curtailment. Each day is represented as a column, with the start and end of the day corresponding to the bottom and top of the column, respectively. Each column comprises 24 ‘bins’, one for each hour of the day. The colour of the bin represents the level of curtailment during that hour, with darker shades meaning more curtailment. This format highlights temporal patterns and variation of curtailment. In this example, four out of seven days were characterised by curtailment during the early morning hours and one period saw prolonged curtailment over two and a half days. We will return to the temporal analysis of curtailment in Section 3.3.

3.2 Validation of wind power simulation

This section validates the model by comparing the model output with historic data. The wind power model will be discussed first, followed by the curtailment model in Section 3.3.

Fig. 3 plots the total hourly wind output from the model against empirical hourly data for wind generation for 2011. A black reference line is included to illustrate a perfect fit. Measured data was available for Republic of Ireland only and sourced from Eirgrid [29]. Installed wind capacity in the Republic of Ireland increased from 1374 MW in January 2011 to 1557 MW in December 2011 [30]. A limitation of the model, however, is that it requires a single value for installed wind capacity for the whole year. A time-weighted average of 1491 MW was therefore used. The model would appear to under-estimate wind output in the middle of the power range, and over-estimate wind output at the high end of the range.

To investigate this further, Fig. 4 shows the same data plotted as a probability density distribution. This confirms the overestimate for high outputs and the underestimate between 40 and 90%. It also illustrates that the model over-estimates wind output at the very low end of the power range. The capacity factor (C_{annual}) for the modelled data is 29.4%, which was calculated from the total modelled wind energy output for the year of the year (E_{tot}), and the total installed wind capacity (N_{national}) as

$$C_{\text{annual}} = \frac{E_{\text{tot}}}{N_{\text{national}} \times 8760 \text{ h}} \quad (9)$$

This value can be compared to the capacity factor of the actual data (31.6%), which has been calculated as a time-weighted

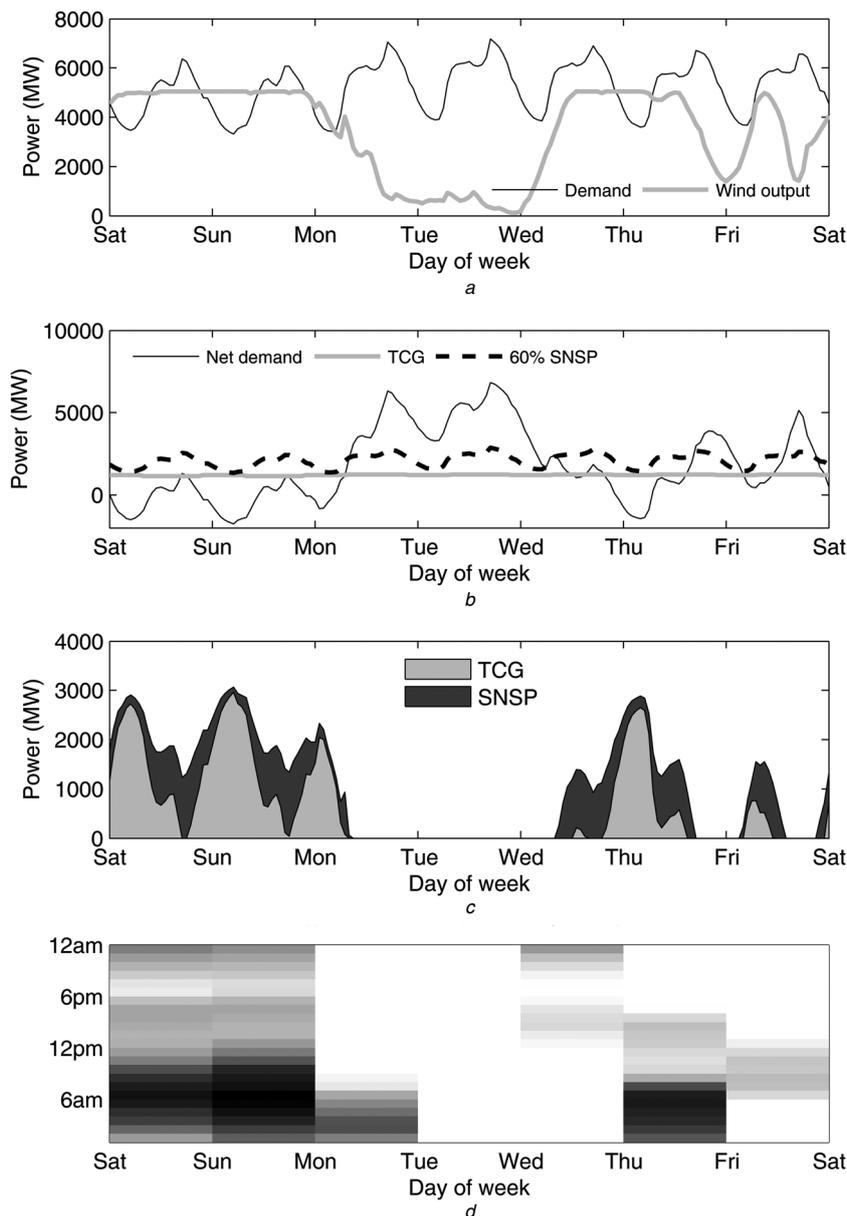


Fig. 2 Operation of model over an illustrative week

- a Demand and wind output for one week in January
- b Net demand and curtailment variables
- c Total curtailment over one week
- d Alternative visualisation of curtailment

average of the reported monthly capacity factors for Republic of Ireland [30]. The authors note that the model underestimates the wind capacity factor by 7%, which could well be explained by the use of the power law method for wind speed extrapolation. The agreement between modelled and measured data is, however, reasonable for the purposes of this paper.

There is, however, a particular need for the model to accurately account for the temporal variability of wind output, so that the model's estimates of the timing of curtailment are realistic. Fig. 5a shows an example of the modelled hourly wind output data compared with actual wind output data for the Republic of Ireland for May 2011. The model appears to capture the broad variations in wind output well, yet over shorter periods of time the model and empirical data can deviate.

As this paper has a particular focus on accurately accounting for the timing of wind output and curtailment, it is important to

explore the temporal accuracy of the wind model. Fig. 5b shows the error between the modelled and measured data for the same month as Fig. 5a. The sum of the square of the error for the month shown in Fig. 5 was 1.05×10^5 MW. For the wind model to be temporally accurate it is important to minimise the error between modelled and measured data. To check if the error between modelled and measured data is a minimum, the sum of the square of the error between modelled and measured data was calculated for the whole year. This calculation was performed using a range of temporal shifts to the modelled data, from 96 h lagging to 96 h leading, as

$$s_t = \sum_h \sqrt{(P_{\text{model},h,t} - P_h)^2}$$

where s_t is the sum of the square of the error for time lag/lead t

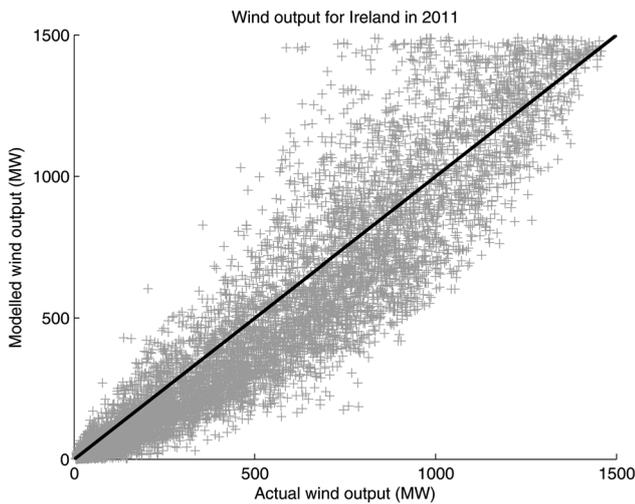


Fig. 3 Modelled wind output using installed wind capacity of 1491 MW against actual measured wind output for Republic of Ireland in 2011

applied to the modelled data, $P_{\text{model},h,t}$ is the modelled wind power output series for each hour h of the year with applied time lag/lead t , and P_h is the measured wind power output.

For the model to have relative temporal accuracy, the error s should be at a minimum at a temporal shift of zero hours, that is, when $s=s_0$, and for the error to increase as the modelled and measured data were increasingly mismatched in time (as $|t|$ increases). Fig. 6 shows the relationship between the error and time lag/lead t . Errors have been normalised to 1, which occurs at the minima at 0 h shift, as

$$s_{\text{norm},t} = \frac{s_t}{s_{t=0}} \quad (10)$$

The scale of the error gives an indication of how well the timing of the modelled data matches the timing of the measured data. Local minima can be observed at 24 h intervals, and the error can be seen to level off after a period of about three days. The figure indicates that the model accurately accounts for the temporal variability of wind output on the All-island system.

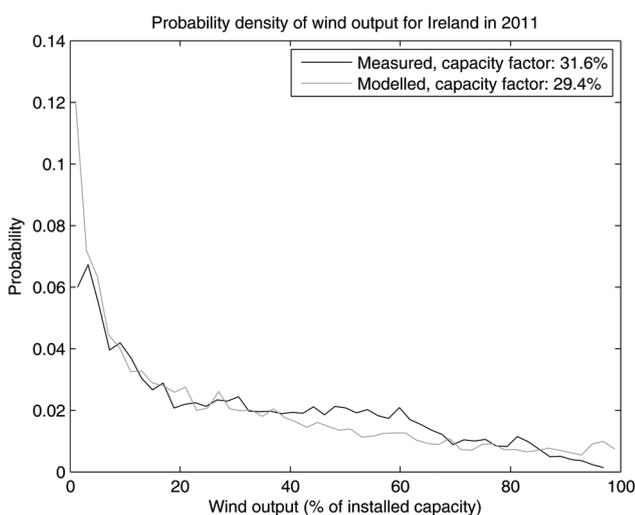


Fig. 4 Probability density of modelled and measured wind output for Republic of Ireland in 2011

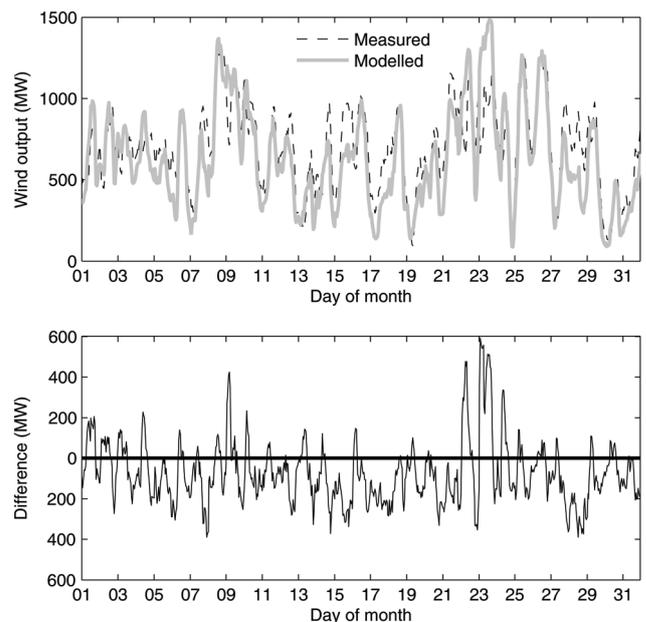


Fig. 5 Measured and modelled wind output for All-island system for May 2011. Measured data from [29]

a Modelled and measured wind output for Iceland for May 2011
b Difference between modelled and measured wind output

3.3 Validation of curtailment model

Table 1 compares the annual curtailment results of the model against actual values for 2011. Annual wind output results are also shown. Actual values are taken from the 2011 Curtailment Report [5] and are All-island values. The value for total annual curtailment of 95 GWh is based on the report's estimate that 80% of the total of 119 GWh of dispatch-down was associated with curtailment. The modelled estimate for curtailment is 87 GWh, calculated using an assumed installed wind capacity of 1897 MW, which is based on a time-weighted average of installed wind capacity for the All-island system as reported in [30]. The model estimates for curtailment are 8 GWh less than the actual reported values, however, when taken as a percentage, the modelled curtailment results are in good

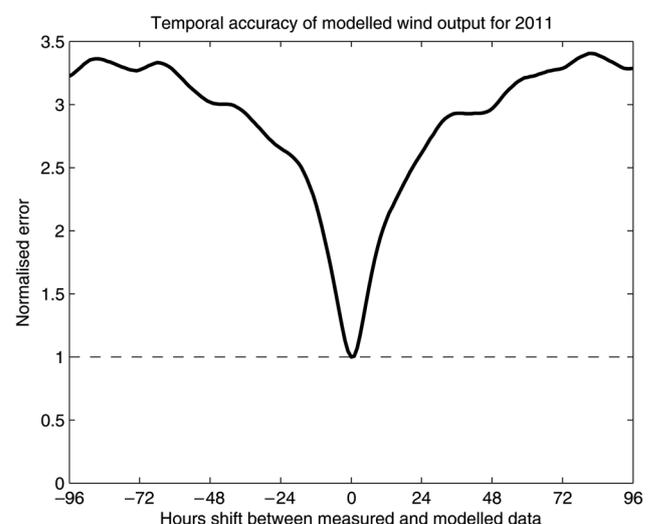


Fig. 6 Temporal accuracy of modelled wind output compared to measured wind output for 2011

Table 1 Modelled wind output and curtailment data compared to actual values for 2011

| | Modelled using 2011 data | Actual 2011 values |
|------------------------------|--------------------------|--------------------|
| total wind generation, GWh | 4880 | 5212 |
| capacity factor, % | 29.4 | 31.6 |
| total wind curtailment, GWh | 87 | ~95 |
| percentage wind curtailed, % | 1.79 | 1.82 |

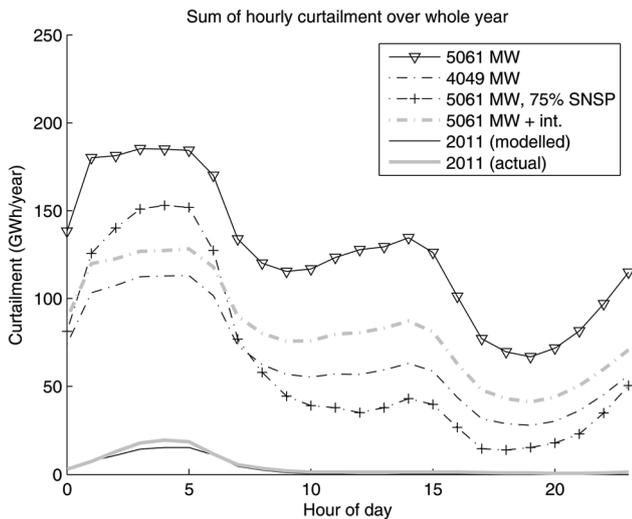


Fig. 7 Distribution of hourly curtailment totals for different scenarios

agreement with the reported values (1.79% for modelled results compared with 1.82% for the measured results). This match should, however, not be taken as a measure of model accuracy. Results for other years may well deviate from reported values by greater amounts.

Fig. 7 compares the sum of hourly curtailments for the model with actual values for 2011 for each hour of the day. The relatively modest amount of energy curtailment in 2011 is shown for comparison. Actual values (grey line) have been taken from the 2011 Curtailment Report [5] and are higher than the modelled values (black line), because they include constraints in addition to curtailment. The timing of model results appears to agree well with the actual values. The projected curtailment for 2020 in Fig. 7 will be discussed in Section 4.2.

The previous sections have shown that the annual totals and timings of the results fit well against actual data, and that the model produces appropriate accuracy for the purposes of this paper. Having developed and validated this model, the next section looks forward to 2020 and characterises the timing of curtailment with a view to considering how to best make use of it with demand response.

4 Results

4.1 Curtailment in 2020

Fig. 8 shows the results of the model simulation for 18 different scenarios, each with different assumptions for the

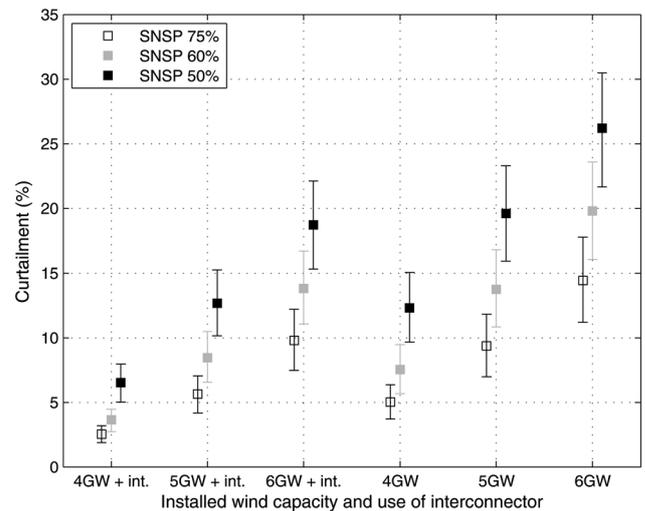


Fig. 8 Effect of installed wind capacity, SNSP limit and interconnection with GB (+ int.) on curtailment levels on the All-island power system

year 2020. It illustrates the effect of installed wind capacity, SNSP limit, use of interconnection with GB, and yearly variation of wind output on curtailment levels. A 5 GW variation to the 5061 MW estimate for installed wind capacity in 2020 mentioned previously. The 4 and 6 GW cases are included to test the sensitivity of curtailment to higher or lower levels of wind capacity. Square data points in Fig. 8 represent mean values over a simulated range of four years, and the error bars the maximum and minimum annual values over this period. These results are also provided in table format in the Appendix.

Curtailment can be seen to increase with increasing installed wind capacity, as well as with decreasing SNSP limit. The use of the 500 MW interconnector considerably reduces curtailment, based on the assumptions mentioned earlier. A 5 GW of wind with SNSP of 75% and use of interconnector results in a mean annual curtailment of 5.6%, and a maximum annual curtailment of 7.0% for the four individual years of data considered here. McGarrigle *et al.* [11] estimated curtailment levels between 6.5 and 7.3% for a comparable scenario of 5193 MW, SNSP 75% and use of interconnection. These values can be seen to be broadly within the range of values shown here.

Overall the results of the present study confirm the findings of McGarrigle *et al.* that there is likely to be a considerable amount of curtailment on the All-island system in the near future – provided nothing is done to address the problem. This highlights the importance of finding practical methods for reducing curtailment, one of which (demand response) is discussed in later sections.

Furthermore, note that the levels of curtailment are such that none of the scenarios explored here meet the target of 37% of demand being supplied by wind (see Table 4 in the Appendix for these results). The following section therefore considers the scope for demand response to improve the utilisation of wind energy.

4.2 Temporal characteristics of curtailment

To investigate the feasibility of the suggestion that demand response could reduce curtailment, it is important to understand when it occurs. Of the 18 scenarios presented in

Fig. 8, the following focuses on four, all of which have demand and wind scaled up to 2020 levels:

- Scenario 1: 5061 MW wind capacity, 50% SNSP
- Scenario 2: 4049 MW wind capacity, 50% SNSP
- Scenario 3: 5061 MW wind capacity, 75% SNSP
- Scenario 4: 5061 MW wind capacity, with use of 500 MW interconnector

Fig. 7, mentioned earlier, illustrates when curtailment occurs throughout the day for the four scenarios. The distribution throughout the day is broadly similar, with more relative curtailment during the day for the 5061 MW 50% SNSP scenario. The 5061 MW 75% SNSP scenario shows that increasing the SNSP has more of an impact in terms of reducing curtailment during the day and less of an impact during the night and early morning. This is because curtailment during the night is predominantly associated with minimum synchronous generation limits (curtailment rule 1 as described in Section 2.3) and not because of the SNSP limit. All scenarios are characterised by a peak of curtailment occurring during the night and early morning, a levelling off during the day, and a trough of curtailment during the evening. Indeed the pattern that emerges is similar to an inverted system demand profile. The use of the interconnector can be seen to reduce curtailment, but not affect the timing of when curtailment occurs.

Although the aggregated view of curtailment shown by Fig. 7 reveals that curtailment occurs predominantly at night, it does not show whether this is consistent from one night to the next, in other words, how regular it is. This is a critical consideration for demand response purposes, and providing a clearer picture of the regularity of curtailment is a novel contribution of this paper. Fig. 9, therefore, provides new insight into the timing of curtailment by showing hourly

curtailment over four years for scenario 3 (5061 MW and 75% SNSP). Each hour of each day is represented by a pixel, with the shading of the pixel representing level of curtailment: black for the highest level, and white for zero.

Four observations to curtailment can be drawn from the data for all of the scenarios. Firstly, curtailment occurs predominantly during the early hours of the morning as this is when demand is at its lowest. Secondly, curtailment tends to occur in 'clusters' that span several days. This is associated with the passing of large weather systems, which results in the variance of wind speed having a peak at a frequency of about four days [31]. Thirdly, curtailment has seasonal variability, with higher levels occurring during the winter months, when wind speeds tend to be higher and finally, there is considerable variability between years. Indeed, across all 18 scenarios considered here the average difference in total curtailment between maximum and minimum years is 57%. The data shown in Fig. 9, along with other curtailment results from the model, have been made publicly available for further investigation [32].

5 Discussion and topics of further investigation

Given the patterns of curtailment seen above, the obvious candidates for practical demand response applications are electric space and water heating. The higher level of curtailment during the winter months, for example, matches up well with the seasonal demand for heat. On a daily basis, demand for heat is during the day, whereas curtailment occurs predominantly at night. Thermal storage may therefore be required to shift heating demand. For space heating, this could be achieved using conventional electric storage heaters, or thermal heat pumps. Indeed it has been shown that demand associated with electrical heating in

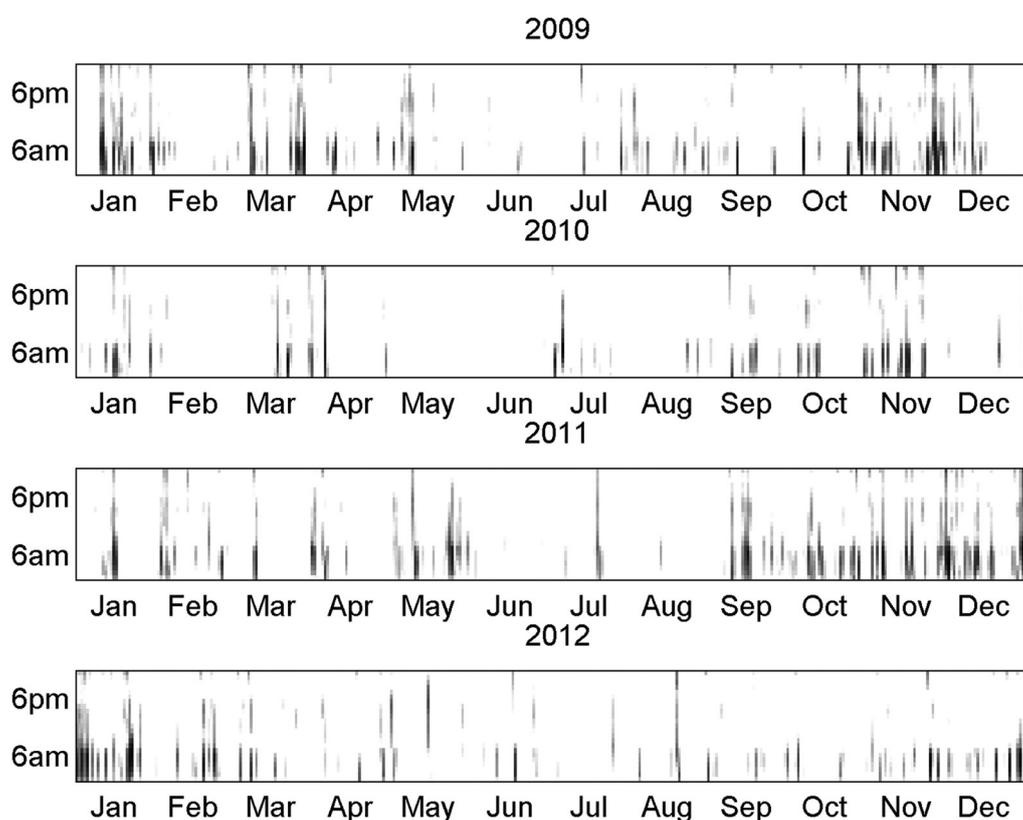


Fig. 9 Curtailment events (dark areas) over a period of four years for 5061 MW wind capacity, 75% SNSP and no use of interconnector

well-insulated dwellings with heat pumps could be shifted by up to 6 h without significant impact on occupant comfort levels [33]. Evidently, shifts of this scale would be useful for making use of curtailment for heating purposes.

Electric space heating is, however, not common in Ireland, and it is conceivable that it might be difficult to motivate consumers to invest in new electric heating systems. A recent survey, however, found that ~77% of households had electric immersion water heaters [34]. It is useful therefore to consider the volume of energy available because of curtailment compared to the volume of demand for water heating.

There are 1.66 million households in the Republic of Ireland [35], and 0.72 million in Northern Ireland [36], giving a total of 2.38 million. Assuming 77% have electric immersion heaters, makes 1.84 million hot water tanks. Assuming each tank holds 120 l of water, or ~120 kg, with a heat capacity for water of 4.2 J/gK, and a potential to be heated a further 20°C, gives 18.5 TJ or 5.14 GWh of energy that could theoretically be used to heat this amount of water once. For comparison, projecting forward to 2020, the 2011 data shown in Fig. 9 resulted in 1.54 TWh of energy curtailed over the whole year, or an average of 4.22 GWh per day, which is similar to the 5.14 GWh of available hot water storage. Technically, therefore, it would be possible to make use of some excess wind generation using existing assets such as electric immersion heaters, and this could mean that payback time of investment costs could be reduced.

Although the values for average curtailment per day and energy storage available in hot water tanks are similar, it should be noted that the average curtailment value masks the considerable variability of daily curtailment. Fig. 10, for example, shows daily curtailment for the same scenario as above, and includes for comparison the 5.14 GWh hot water value. Although there are many days where curtailment could be used for hot water, there are evidently also many days where there is considerably more curtailment than could be feasibly used for this purpose. To reduce curtailment on these days, additional demand response measures would therefore be required.

The authors note that the predominant occurrence of curtailment at night could match well with future charging patterns of electric vehicles. The expected electrification of transport, by increasing demand at night, may well therefore provide an effective means for reducing curtailment, albeit

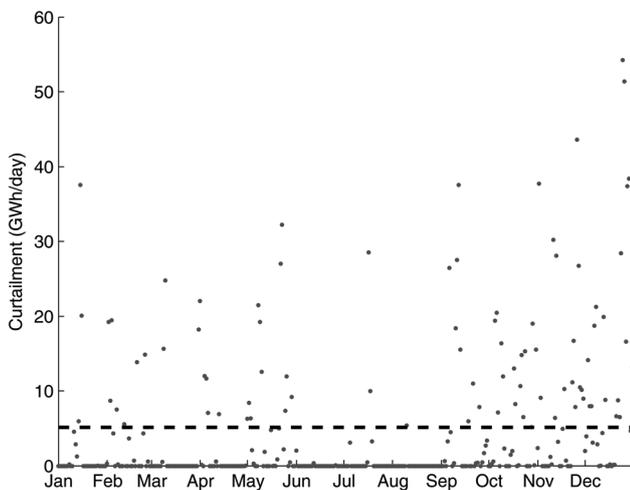


Fig. 10 Daily curtailment totals for 5061 MW wind with 75% SNSP (2011 data)

one that would require considerable investment in terms of vehicles and charging points (unlike the use of electric immersion heaters which are already installed in 77% of dwellings).

A potential challenge highlighted by the results is that levels of curtailment vary considerably from year to year, which will introduce variability to the expected returns for consumers seeking to benefit from cheap electricity because of curtailment. A potential topic for future research therefore would be to quantify how much consumers might be expected to save on electricity bills given investment in technology to facilitate demand response to curtailment signals. It is also worth noting that while the conventional approach is to shelter the consumer from such forms of risk, it has been suggested that there is considerable scope to engage the consumer with the challenges of balancing the system [37].

More broadly the results of this paper highlight the value of 'dual-fuel' heating systems, for example, a gas boiler which can be used to provide space and water heating, as well as electric immersion heaters and portable electric radiators. Consumers with dual-fuel systems are able to shift back and forth to electricity depending on which fuel is cheapest at the time. The curtailment results shown previously indicate the availability of cheap electricity because of excess wind generation can vary stochastically, in which case there is value in being able to take advantage of cheap electricity when it is available, and switching to the alternate fuel during periods when wind output is low. This raises the important question for energy policy of whether we should commit to a more efficient but potentially less flexible all-electric future for heating, or focus more on developing dual-fuel systems, which are already relatively common in many people's homes.

6 Conclusions

This paper has presented a model for estimating curtailment on the All-island power system in 2020, using historic high resolution wind speed and demand data covering four years (2009–2012), and a set of curtailment rules. The model was validated using historic wind output and curtailment data for 2011.

For the four years of data considered here, estimates of mean curtailment levels in 2020 are in the range 5.6–8.5% for 5061 MW installed wind capacity and 500 MW of interconnection available for export to GB, across the expected range of SNSP limits (75–60%). In addition, this study has shown that none of the scenarios reach the target of meeting 37% of demand from wind and that demand response may be necessary to improve utilisation.

The majority of curtailment was found to occur during the night and in the early hours of the morning due to the low demand at these times. Increasing SNSP limit was found to reduce curtailment, but does so predominantly during the day, which still leaves the problem of considerable curtailment during the night and early hours of the morning.

Curtailment was also found to exhibit stochastic variability, for example, by occurring in 'clusters' lasting several days, occurring more during winter than summer, and by varying considerably from year to year. All of these are because of the fact that curtailment is dependent on the stochastic nature of the wind resource.

To make practical use of excess wind generation, electric water heating was found to be worthwhile given the

existing high penetration of systems, and the planned roll out of smart meters which could provide the necessary communications infrastructure. There is the risk, however, that hot water tanks will not provide enough storage for clusters of curtailment over several days, in which case there is a value in solutions with larger storage capacities. 'Dual-fuel' heating systems, where electricity can be used for heat during periods of excess wind, and an alternate fuel used when electricity becomes expensive, could become valuable in such future systems.

7 Acknowledgments

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9 Appendix

See Tables 2–4.

Table 2 Model results for curtailment without use of interconnector

| | 4049 MW | 5061 MW | 6073 MW |
|------|---------|------------------------|---------|
| SNSP | | mean curtailment, % | |
| 50% | 12.3 | 19.6 | 26.2 |
| 60% | 7.5 | 13.7 | 19.8 |
| 75% | 5.0 | 9.4 | 14.4 |
| | | maximum curtailment, % | |
| 50% | 15.1 | 23.3 | 30.5 |
| 60% | 9.5 | 16.8 | 23.6 |
| 75% | 6.4 | 11.8 | 17.8 |
| | | minimum curtailment, % | |
| 50% | 9.6 | 15.9 | 21.6 |
| 60% | 5.7 | 10.8 | 16.0 |
| 75% | 3.7 | 7.0 | 11.2 |

Table 4 Model results for percentage of demand supplied by wind (without use of interconnector)

| | 4049 MW | 5061 MW | 6073 MW |
|------|---------|------------------------------------|---------|
| SNSP | | mean demand supplied by wind, % | |
| 50% | 21.5 | 24.7 | 27.1 |
| 60% | 22.7 | 26.5 | 29.5 |
| 75% | 23.4 | 27.8 | 31.5 |
| | | maximum demand supplied by wind, % | |
| 50% | 24.0 | 27.3 | 29.8 |
| 60% | 25.4 | 29.5 | 32.7 |
| 75% | 26.2 | 31.2 | 35.1 |
| | | minimum demand supplied by wind, % | |
| 50% | 18.2 | 21.2 | 23.7 |
| 60% | 19.0 | 22.5 | 25.4 |
| 75% | 19.4 | 23.5 | 26.9 |

Table 3 Model results for curtailment with use of interconnector

| | 4049 MW | 5061 MW | 6073 MW |
|------|---------|------------------------|---------|
| SNSP | | mean curtailment, % | |
| 50% | 6.5 | 12.7 | 18.7 |
| 60% | 3.6 | 8.5 | 13.8 |
| 75% | 2.5 | 5.6 | 9.8 |
| | | maximum curtailment, % | |
| 50% | 8.0 | 15.3 | 22.1 |
| 60% | 4.5 | 10.5 | 16.7 |
| 75% | 3.2 | 7.0 | 12.2 |
| | | minimum curtailment, % | |
| 50% | 5.0 | 10.1 | 15.3 |
| 60% | 2.7 | 6.6 | 11.1 |
| 75% | 1.9 | 4.2 | 7.5 |