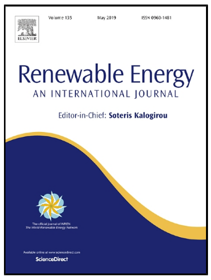
Sunny windy Sundays

Drew, D. R., Coker, P. J., Bloomfield, H. C. ORCID: https://orcid.org/0000-0002-5616-1503, Brayshaw, D. J. ORCID: https://orcid.org/0000-0002-3927-4362, Barlow, J. F. and Richards, A. (2019) Sunny windy Sundays. Renewable Energy, 138. pp. 870-875. ISSN 0960-1481 doi: https://doi.org/10.1016/j.renene.2019.02.029 Available at https://centaur.reading.ac.uk/82089/

Accepted Manuscript



Sunny Windy Sundays

Daniel R. Drew, Phil J. Coker, Hannah C. Bloomfield, David J. Brayshaw, Janet F. Barlow, Andrew Richards

PII: S0960-1481(19)30173-9

DOI: 10.1016/j.renene.2019.02.029

Reference: RENE 11161

To appear in: *Renewable Energy*

Received Date: 28 September 2018

Accepted Date: 06 February 2019

Sunny Windy Sundays

Daniel R. Drew[1*], Phil J. Coker[2], Hannah C. Bloomfield[1,3], David J. Brayshaw[1,3], Janet F. Barlow[1] and Andrew Richards[4]

[1] Department of Meteorology, University of Reading, Reading, UK
[2] School of Construction Management and Engineering, University of Reading, Reading, UK
[3] National Centre for Atmospheric Science, Department of Meteorology, University of Reading, Reading, UK
[4] National Grid, UK

* Author to whom correspondence should be addressed; E-Mail: d.r.drew@reading.ac.uk; Tel.: +44 (0)118 378 7696

Abstract

Rapid expansion of wind and solar capacity in Great Britain presents challenges for managing electricity systems. One concern is the reduction in system inertia during periods where renewables provide a high proportion of demand which has led to some networks imposing system non-synchronous penetration limits. However, given the lack of operational data, the relationship between renewable generation and demand for the full range of meteorological conditions experienced in Great Britain is poorly understood. This study uses reanalysis datasets to determine the proportion of demand from renewable generation on an hourly resolution for a 36-year period.

The days with highest penetration of renewables tend to be sunny, windy weekend days between May and September, when there is a significant contribution of both wind and solar generation and demand is suppressed due to human behaviour. Based on the current distribution of wind and solar capacity, there is very little curtailment for all system non-synchronous penetration limits considered. However, as installed capacity of renewables grows the volume of generation curtailed also increases with a disproportionate volume occurring at weekends. The total volume of curtailment is highly dependent on ratio of wind and solar capacity, with the current blend close to the optimum level.

KEYWORDS: Wind, Solar, Demand, Curtailment, Reanalysis

1.0 Introduction

To meet ambitious carbon reduction targets, global renewable energy deployment has expanded dramatically, with wind and solar generation significantly outpacing other low carbon energy options [1]. The preferred renewable technology has been strongly influenced by local climatic conditions. However a combination of policy incentives and falling costs have seen growing levels of solar generation accompanying wind, even in high latitude systems where solar was once considered non-favourable due to its relatively modest mean output. This is typified by the UK, which is one of the global leaders of wind power with an installed capacity of 17.9 GW (as of June 2017) and has experienced a rapid expansion of solar capacity from only 2.8 GW in 2013 to 12.5 GW in June 2017 [2]. As a result wind and solar now provide approximately 15% of the UK annual electricity requirement [3]. However, on shorter time scales the penetration of renewables can be significantly higher. For example, on Sunday 11th June 2017 wind and solar provided approximately 37% of the total daily demand (excluding embedded conventional generation), with a peak penetration of 47.0% occurring for the 30-minute period between 14:00 and 14:30 [4].

One strand in a wide range of studies addressing renewable intermittency arises from a concern that excess renewable generation may need to be curtailed, meaning wasted investment and increased system costs. It is widely recognised that curtailment could result from system wide renewable excess, localised network constraints or system security concerns. [5, 6, 7, 8]. A particular security concern regards the risk to system stability which can arise at less extreme renewable generation levels, now being reached in certain island and national power systems [9, 10, 11, 12]. Non-synchronous generation, including most wind and solar installations, does not provide the direct inertia that AC power systems have conventionally gained from synchronously coupled thermal generating plant. Without such inertia, stability is reduced and power systems risk rapid, damaging frequency excursions if supply and demand becomes unexpectedly unbalanced [13]. The implementation of System Non Synchronous Penetration (SNSP) limits provides one means to control this risk [11], at the potential expense of increased curtailment.

Several System Operators have imposed specific SNSP thresholds [9, 10] but these can be expected to be raised over time as experience is gained operating with high levels of renewables. There are also other actions that can be taken to preserve system security, albeit typically with some level of increased cost. For Great Britain, System Operator (National Grid) has not currently implemented any specific SNSP limit but is procuring an increasing level of fast acting response services to manage system stability [14] alongside a variety of other current and future measures to ensure system operability [15].

For Great Britain, given the rapid expansion of both wind and solar capacity, the possible penetrations of renewables which could occur is unclear as observed data is only available for a relatively short period of time, during which the capacity has been changing. An understanding of when the high penetrations occur is also vital for the design of time of use tariffs and demand response and flexibility provisions. Furthermore, there is need to determine how the penetration of renewables will be exacerbated in the coming years due to the planned expansion of wind and solar capacity, as outlined in National Grid's Future Energy Scenarios [16]. Based on a range of possible scenarios, the combined solar and wind capacity could increase to between 56.7 GW to 80.1 GW by 2030.

The aim of this study is to determine the penetration of renewables over a comprehensive range of meteorological conditions and scenarios. To achieve this, long term and self-consistent hourly time series of wind power, solar power and demand are produced from meteorological reanalysis data. The derived data enables the characteristics of the power system to be determined including (1) the volume of curtailment for a range of SNSP thresholds (2) when curtailment is likely to occur (in terms of season and time of day) and (3) how the characteristics of curtailment will change as the capacity of wind and solar increases, with a particular focus on the impact of the ratio of wind to solar capacity.

2.0 Method

Studies investigating the integration of renewables typically simulate the power system for a range of penetrations of wind and solar power production and evaluate the impact on the system [17, 18, 19, 20]. One key requirement is a long term dataset in order to capture the wide range of meteorological conditions which can affect the system. Recent work has used global reanalysis data to simulate wind and solar power over a period of over 30 years for specific countries [21, 22, 23, 24]. Such datasets enable the variability of renewable generation to be quantified for a range of temporal scales. Recent work combined datasets with demand data to consider the increasing impact of weather on electricity supply and demand [25, 26].

This study uses reanalysis data to derive an hourly time series of GB-aggregated wind and solar power (based on the current distribution of wind farms and solar panels) and electricity demand for the period 1980-2015 using well-established methods (each model is described briefly below). The data used in this study are freely available for download from the University of Reading Research Data Archive [27]. The hourly proportion of demand provided by renewables, RE_{prop}, is determined using equation 1:

$$RE_{prop}(t) = \left(\frac{Wind\ power\ (t) + Solar\ power\ (t)}{Demand(t)}\right) \times 100\ \% \qquad (1)$$

The derived time series is then analysed to determine the contribution of renewable generation to demand for daily and annual averaging periods, and the volume of curtailment.

The level of wind power curtailment is dependent on a number of network constraint factors including, the transmission, capacity of power lines, maintenance requirements and regional system requirements [5]. However, in this study curtailment is only dependent on the system's capability to safely operate with certain percentage of its generation from non-synchronous generation. A system non-synchronous penetration limit (SNSP) may be imposed by the TSO to prevent an exceedance of a certain percentage of total generation by non-synchronous sources at any one time. For each hour in the time series, if the hourly penetration of wind and solar power exceeds this threshold then the excess volume of renewable energy is curtailed. This study therefore does not include the imports and export of electricity via interconnectors in the SNSP calculation. This should be seen as a measure of system stress, rather than an absolute predictor of discarded renewable generation. In this study, the SNSP limit is varied from 40% to 100%.

2.1 Wind power model

Following the method of Cannon et al. [21] and Drew et al. [22], an hourly time series of GB-aggregated wind power generation spanning the period 1980–2015 is derived using a reanalysis dataset (Modern-Era Retrospective Analysis for Research and Applications dataset (MERRA). MERRA provides hourly gridded wind-speeds at heights of 2 m, 10 m, and 50 m at a resolution of 0.65° x 0.5°. The wind speeds on each level are bi-linearly interpolated horizontally to each wind farm's location. The wind speed is then vertically extrapolated to the turbine hub height, assuming a logarithmic change in wind speed with altitude. The hub-height winds are converted to wind farm normalised power output using a non-linear transform function (the so-called 'wind power curve') and multiplied by the installed capacity to produce an estimate of power output from the wind farm. Finally, the power output of each wind farm is summed over all the wind farms in Great Britain to produce an hourly time-series of GB-aggregated wind power generation. The model has been applied for the current wind farm distribution in Great Britain (as of June 2017) which has a total capacity of 16.9 GW including 5.7 GW located offshore. A complete description of the methodology – and extensive discussion of its validation – is provided in Cannon et al. [21].

2.2 Demand model

Following the method described in Bloomfield et al. [6], an hourly time series of electricity demand for Great Britain was derived for the same 36-year period (1980-2015). The model was developed on a daily resolution using a regression based technique which is then downscaled to an hourly resolution using a seasonally varying diurnal cycle.

The daily mean demand is determined using a multiple linear regression with daily average meteorological and non-meteorological parameters trained against recorded demand data from 2006-2015. The daily mean 2m temperature from MERRA is spatially averaged over Great Britain and used to create an *effective temperature*, which is the meteorological explanatory variable. The model also takes into account non-meteorological demand drivers, including the weekly cycle of demand, national holidays and long-term fluctuations due to changes in GDP, population growth and energy efficiency.

The daily-mean demand data is downscaled to hourly resolution using a linear combination of four prescribed seasonal diurnal cycles. For example, the daily-mean demand for 1st December is downscaled using a 50%-50% weighting of the diurnal curves derived from SON and DJF hourly data. Full details of the model including the regression coefficients and its validation are given in Bloomfield et al. [6].

2.3 Solar power model

The MERRA reanalysis has also been used to derive an hourly time series of GB-aggregated solar PV generation based on the current distribution of solar panels (capacity 12.5 GW as of June 2017). This has been achieved by dividing Great Britain into 9 regions (see Figure 1) and determining the spatially-averaged, hourly mean global irradiance and air temperature for each region.

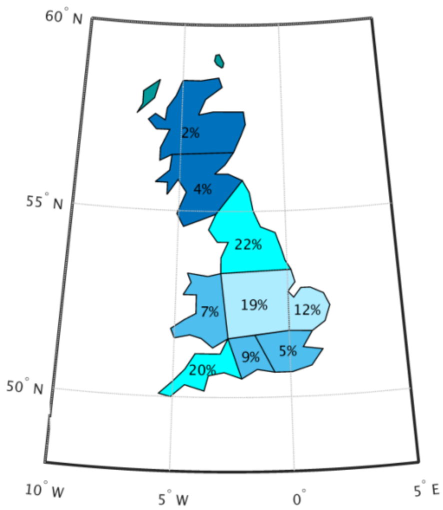


Figure 1 Distribution of solar PV capacity across 9 regions in Great Britain.

In each region, the derived hourly irradiance and temperature data have been compared to observations obtained from Met Office weather stations. In all 9 regions, MERRA tends to overestimate the irradiance, this result is in agreement with the findings of Boilley and Wald [28] that reanalyses tend to have too many clear-sky days compared to observations. A quantile-quantile bias correction has therefore been applied to the regional irradiance data. For temperature, MERRA generally provides a good representation of the hourly variability for each region.

The regional data have been combined to produce an hourly GB-mean irradiance, I_{GB} which is weighted by the solar capacity in each region, using equation 2

$$I_{GB}(t) = \frac{\sum_{i=1}^{n} C_i(t) \times I_i(t)}{\sum_{i=1}^{n} C_i(t)} \quad (2)$$

where I_i is the irradiance (in Wm^{-2}), C_i is the installed capacity of solar PV of each of the regions (n=9) and t is the time. A similar method has been used to determine an hourly GB-mean temperature, using equation 3.

$$T_{GB}(t) = \frac{\sum_{i=1}^{n} C_i(t) \times T_i(t)}{\sum_{i=1}^{n} C_i(t)} \quad (3)$$

where T_{GB} is the capacity weighted mean air temperature (in °C).

For the current distribution, the capacity of each region has been estimated using the feed-in tariff register which outlines the location of each PV system in GB (receiving subsidy) on a local authority resolution [29]. The weightings for each region are shown in Figure 1.

2.3.1 Multi-linear regression model

The hourly mean PV generation is determined using a multiple linear regression technique with the hourly GB-mean irradiance and temperature trained against PV generation data for a two year period (2014-2015). The model also includes dummy variables for the time of day and season to take into account the angle of the sun and panel orientation.

The regression model created has the form:

$$PV(t) = \alpha_1 + \alpha_2 I_{GB}(t) + \alpha_3 T_{GB}(t) + \sum_{k=4}^{6} \propto_k SEASON(t) + \sum_{i=7}^{11} \propto_i TIME(t) \quad (4)$$

where PV(t) is the GB-aggregated solar capacity factor at time t,. The α's are regression coefficients. α_2 and α_3 correspond to the coefficients for meteorological drivers of solar PV generation; solar irradiance and temperature. α_4 to α_{11} are coefficients of binary values accounting for the season and time of day. The magnitude of the derived parameters is given in Table 1. The performance of the model has been evaluated using observed solar PV generation data for 2016. At an hourly resolution, the solar model performs well with R^2=0.96 (coefficient of determination) and Mean Absolute Error (MAE) =3.1%. For the daylight hours only, R^2=0.94 and MAE=5.6%.

Table 1 Solar PV model regression coefficients for the training period 2014-2015. The terms are described as in equation 4.

Regression parameter	Variable	Value
α_1	Intercept	0.853
α_2	Irradiance	0.093

α_3	Temperature	0.089
α_4	Season- MAM	0.178
α_5	Season- JJA	-3.118
α_6	Season- SON	-0.477
α_7	Time 06:00-08:00	0.976
α_8	Time 09:00-11:00	2.556
α_9	Time 12:00-14:00	0.0
α_{11}	Time 15:00-17:00	0.169
α_{12}	Time 18:00-23:00	-0.718

3.0 Results

3.1 Daily variability of demand and renewable generation

Each day in the 36-year period has been categorised based on the terciles of total renewable generation (i.e. wind and solar generation) and electricity demand and therefore results in possible 9 modes. This analysis uses the demand data which contains the daily variability. Figure 2 shows the frequency of occurrence of each grid mode as a function of month averaged across the 36-year period. The modes associated with high demand predominantly occur in winter, (92% of high demand days occur between November and March) and those associated with low demand days generally occur in summer (82% between May and September). However, due to the suppression of demand on weekends, there are a number of low demand days in all months of the year with the exception of February. Consequently, the days when the system is categorised as low demand and high renewable generation can occur throughout the year but predominantly in summer.

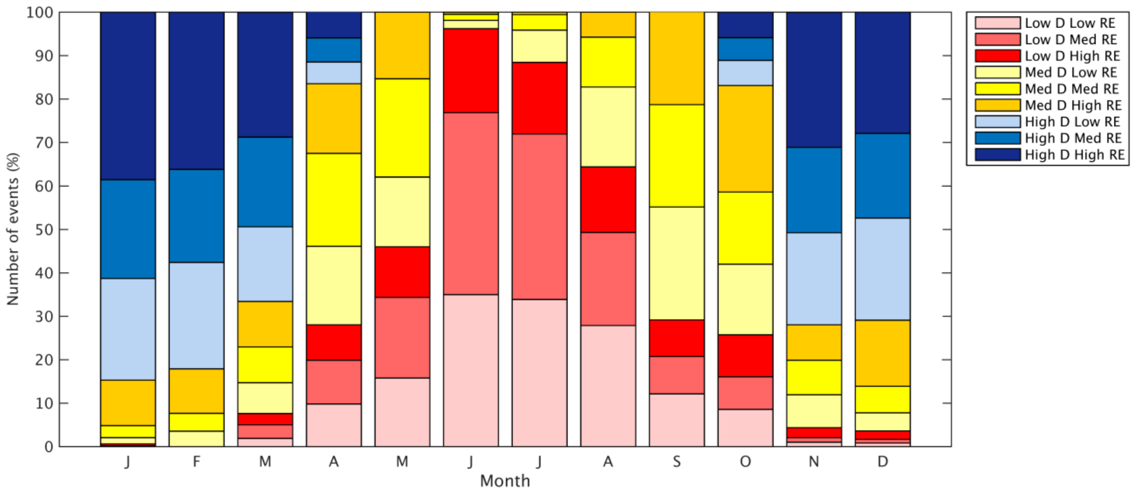


Figure 2 The frequency for which each electricity system mode occurs in each month.

Over the 36 years, there are 1057 days classified as low demand and high renewables. Figure 3(a) shows that approximately 53% of these days occur between June and August when demand is relatively low due to warmer summer temperatures (therefore reduced demand for heating). During this period, the events can occur on both weekends and weekdays, but there are a disproportionate number on the weekend (58.3% weekends and 41.7% weekdays; see Figure 3a). However, the winter events only occur on weekends when the level of demand is suppressed, particularly on Sundays. Figure 3(b) shows that the most extreme cases (i.e. when the renewable generation is above the 90th percentile and demand is below the 10th percentile) occur predominantly in the transition months (May and September) when there are relatively high levels of both wind and solar resource and only on weekends.

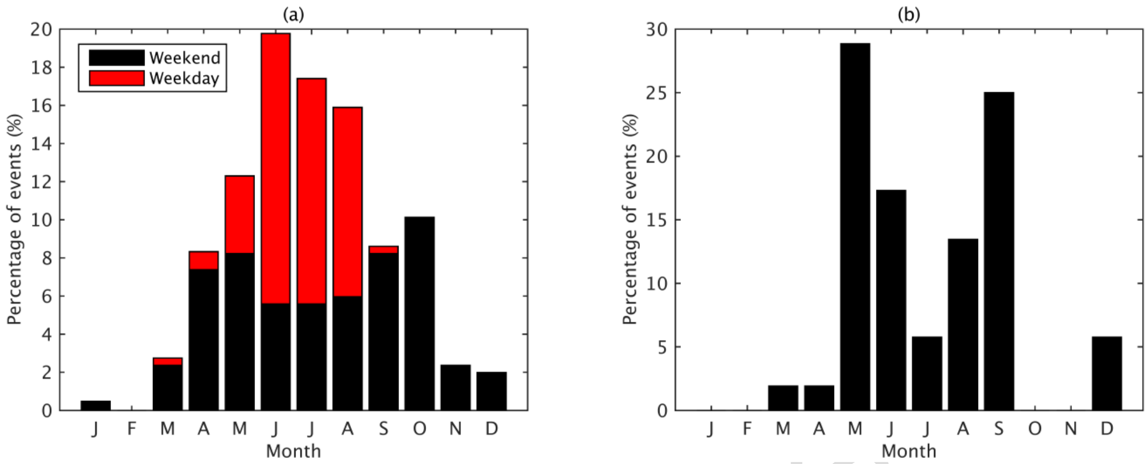


Figure 3 The frequency of high renewable low demand days which occur in each month.(a) Demand <p33.3 and Renewable generation>p66.6 (b) Demand <p10 and Renewable generation>p90.

3.2 Peak renewables penetration day

For each year, the day with the highest contribution from renewables has been determined. Across the 36 years, this value varies from 43.9% for the weather conditions in 2001 to 57.2% for the weather conditions in 2003, with an average value of 48.9% (see Figure 3). Generally this day occurs during the transition months of spring and autumn (for 17 of the years the peak renewables day occurred in either April or September). In addition, Figure 4 shows that of the peak renewable days 31 occur on weekends (20 Sundays) when the demand is low.

The days with high proportions of renewable generation are therefore driven by meteorological conditions and the day of the week. The aim of this paper is to investigate the highest possible penetrations of renewables for a comprehensive range of meteorological conditions as recorded over a 36 year period. It is therefore important to account for the fact that cycles of human behaviour- such as working weeks- are not weather-dependent. The current GB power system may therefore have been historically fortunate if the meteorological conditions leading to largest wind and solar power generation have fallen on days with above average demand (i.e. weekdays rather than weekends). To ensure the highest possible renewable penetrations are observed, an additional demand time-series is created such that every day is representative of a Sunday (i.e., the day of lowest demand throughout the week).

The peak renewable penetration day for each year has been recalculated using the Sunday equivalent demand data. This can be considered as the peak renewable day for each year if the same weather conditions had occurred but happened to fall on a Sunday. Figure 4 shows this leads to an increase in the peak renewables penetration for all but three years. As a result, there is an increase in the peak penetration day across the 36 years to 60.8% (experienced in 1996). It is likely that curtailment of renewable generation would be required on days with these high penetrations of renewables, this is discussed in the following section.

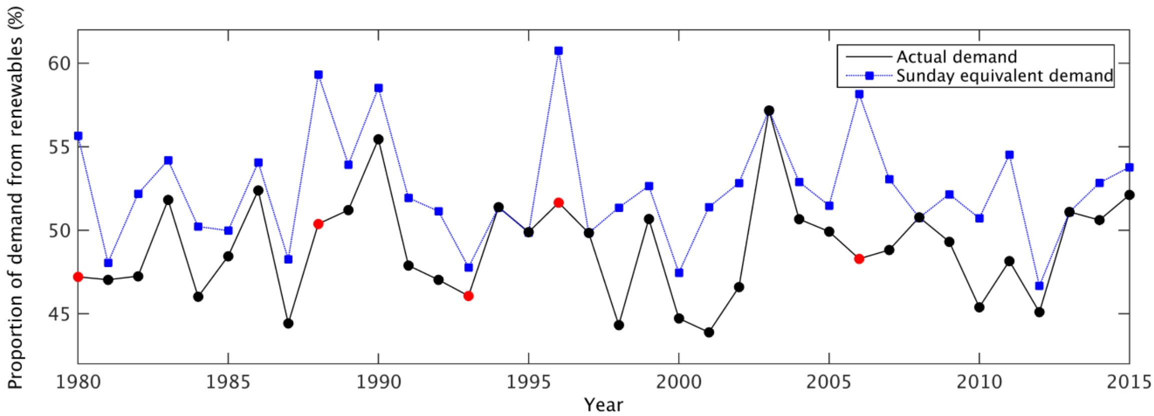


Figure 4 The day with the highest penetration of renewables for each year based on the demand data with the weekly cycle (black) and the Sunday equivalent demand (blue). The red dots indicate events which did not occur on a weekend.

3.3 Curtailment

The 36 year hourly time series of the penetration of renewables (RE_{prop} from Section 2) has been analysed to determine the volume of renewable energy curtailed for a range of assumed SNSP limits. Based on the current capacity of wind and solar, there is very little curtailment for all SNSP limits considered (see Figure 5a). For example with the lowest SNSP threshold tested of 40%, only 1.5% of total renewable generation is curtailed – this equates to 955 GWh per year. Of the amount curtailed, a disproportionate amount (55%) occurs on weekend days due to the reduced demand. As the SNSP limit increases to 50%, the amount of curtailment decreases to only 0.2% of total renewable generation or 120 GWh per year with an even higher proportion occurring at the weekend, 77.4%.

Over the coming years there will be continued growth in renewables in Great Britain, this section therefore estimates how the level of curtailment changes as the capacity of wind and solar increases. Two future scenarios have been considered (see Table 2). For both scenarios it is assumed that the current ratio of wind to solar capacity remains unchanged (i.e. 43% solar and 57% wind) along with the spatial distribution of the capacity. In the first scenario, wind and solar contribute an average of 25% of total electricity demand over the 36 year period. To meet this value, the capacity of solar and wind is required to increase to 15.7 GW and 22.5 GW respectively. For the second scenario, wind and solar contribute an average of 30% of total electricity demand over the 36 year period corresponding to the capacity of solar and wind increasing to 18.8 GW and 27.0 GW respectively.

Table 2 Details of the two future scenarios.

	Proportion of total demand (%)	Wind capacity (GW)	Solar capacity (GW)
Scenario 1	25	22.5	15.7
Scenario 2	30	27.0	18.8

Figure 5 (b) and 5 (c) show as the capacity of renewables increases, the volume of renewable generation curtailed also increases. For scenario 1, with a non-synchronous limit of 50% there is an average curtailment of 1249 GWh (1.6% of total RE generation) of which 54% occurs on weekends. In comparison, for scenario 2, there is an average curtailment of 4501 GWh (4.8% of total RE generation) of which 44% occurs on weekends.

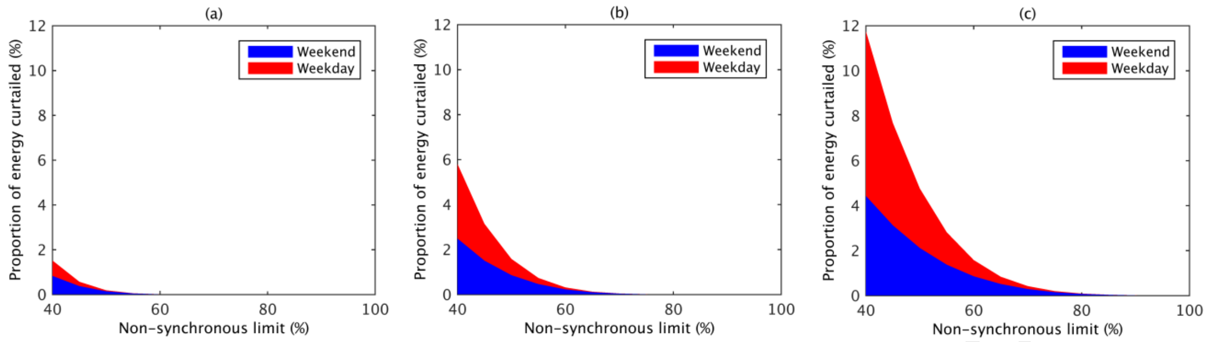


Figure 5 The proportion of renewable generation curtailed as a function of non-synchronous penetration limits. (a) Current distribution of wind and solar capacity (b) Future scenario 1: Renewable generation contributes 25% of total demand and (c) Future scenario 2.: Renewable generation contributes 30% of total demand.

3.3.1 Impact of wind and solar capacity

Section 3.3 considered the level of curtailment for future scenarios of renewable capacity assuming a constant ratio of wind to solar capacity. However, this ratio could change depending on the future uptake of each of the technologies; therefore this section investigates the volume of curtailment for a full range of possible ratios of wind to solar capacity. For each ratio, the capacity in wind and solar has been adjusted to maintain the requisite level of renewable generation as a proportion of demand over the 36 year period (i.e. 25% of demand for scenario 1 and 30% of demand for scenario 2). Due to the differences in capacity factor between wind and solar, systems with higher proportion of solar require higher levels of capacity to maintain the total energy generation. For example, to maintain the energy requirement for scenario 1, a solar only system requires 80.3 GW of capacity, in comparison to 27.9 GW of capacity for a wind only system.

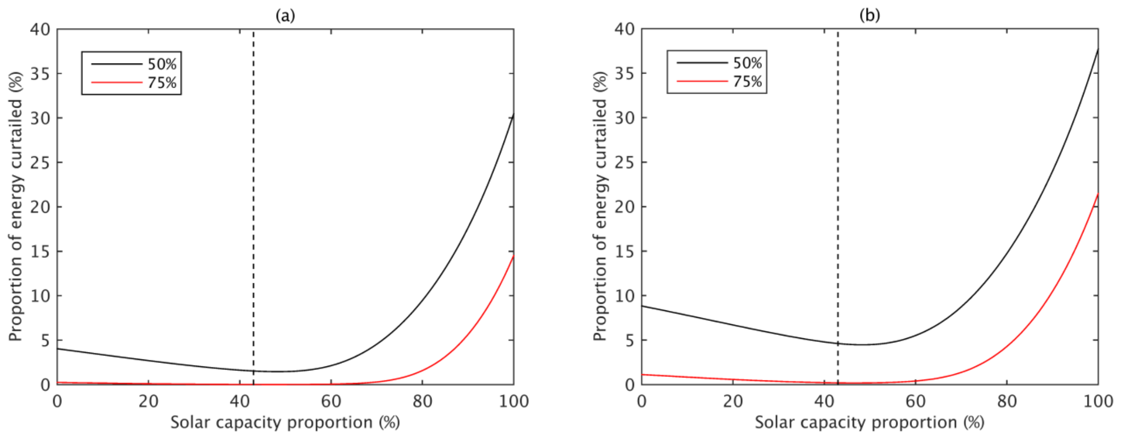


Figure 6 The proportion of renewable generation curtailed as a function of the ratio between wind and solar capacity. Data is shown for two SNSP limits (50% and 75%) and for two future scenarios (a) renewables provide 25% of total demand and (b) renewables provide 30% of total demand.The dashed line indicates the current ratio between wind and solar capacity in Great Britain.

Figure 6 shows the level of curtailment for two values of the SNSP limit (50% and 75%) as a function of the proportion of solar capacity. A similar relationship is shown for all of the scenarios considered. When the renewable capacity is 100% wind (i.e. solar capacity is zero), curtailment is relatively low though not at its minimum level. For example, for scenario 1 when the SNSP limit is set to 50%, only 4.0% of renewable generation is curtailed. As the proportion of solar capacity increases, the level of curtailment decreases and reaches a minimum value of 1.5% at a blend of 48% solar and 52% wind. As the proportion of solar capacity increases further, the level of curtailment increases rapidly and peaks at 100% solar with 30.5% of renewable generation curtailed. From the perspective of minimising the curtailment, the current blend of wind and solar (43% solar) is therefore close to the optimal level.

3.3.2 When does curtailment occur?

To understand the relationships shown in Figure 6 it is important to consider when the curtailment occurs. This section determines the volume of curtailment as a function of time of day and season for scenario 2 (30% of demand provided by renewables) and a 50% non-synchronous penetration limit. Figure 7 shows when the curtailment occurs for a renewables capacity of 100% solar, 100% wind and the current blend (57% wind and 43% solar). For the 100% solar system, as expected the majority of curtailment occurs in summer (54.5%) and spring (35.1%) with the peak occurring at noon. In contrast, for the wind only system, the majority of curtailment occurs in autumn (30.8%) and winter (40.5%) and predominantly overnight (67% occurs between 1800 and 0600) when the demand is lower.

For the current ratio of wind to solar capacity, the curtailment is approximately evenly split across the four seasons; DJF=26.5%, MAM=26.3%, JJA=20.2% and SON 27.1%.There are clearly two peaks in the diurnal pattern of the curtailment. The first during night time which occurs in all seasons (but mainly in SON and DJF) is driven by wind generation. The second during daylight hours (peaking at midday), occurs in all seasons but predominantly in spring (MAM) and summer (JJA), which is driven by a combination of both the wind and solar generation

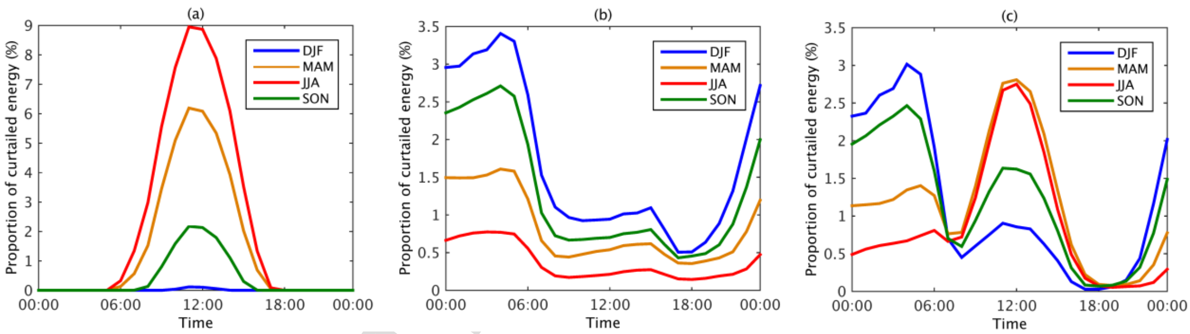


Figure 7 The proportion of renewable generation curtailed as a function of time of day. The analysis is based on a 50% SNSP limit and a future scenario with 30% of demand provided by renewables. (a) system with 100% solar capacity (b) system with 100% wind capacity and (c) system with the current ratio of wind to solar capacity. For each plot the sum of all hours and seasons is 100%.

4.0 Conclusions

In recent years there has been a significant expansion in the capacity of both wind and solar power in Great Britain. As a result, the system operator is observing days where a high proportion of the electricity demand is provided by renewables. This has led to concerns regarding system stability due to reduced levels of inertia. However, for temperate climates like Great Britain with high capacities of both wind and solar, it is unclear as to when the high penetration events occur. This study has developed a framework method which allows the characteristics of the national demand and renewable generation to be examined for a range of scenarios (i.e. changes in wind and solar capacity and/or the ratio of wind and solar capacity). The results show that long term weather analysis is essential when considering instantaneous peaks and for putting recent system experience into context, reinforcing the findings of [6, 23].

System operators are already paying increased attention to high renewable, low demand conditions. This need will increase in the future and should be planned for. Based on the current capacity of renewables, the infrequent nature of high penetration events indicates that some level of curtailment would be the most effective remedy for maintaining system stability. However, more frequent events occur as the installed capacity of renewables increases (indicated in Figure 4), which would represent either lost revenue to the generators, or a significant cost to the System Operator given the current market environment.

For a country like the UK weekends can be particularly challenging, especially Sundays. Across the 36 years investigated, the days with the highest penetration of renewables tend to be sunny, windy weekend days between May and September. This is when there is a significant contribution of both wind and solar generation and the demand is suppressed due to human behaviour. For the period of 1980-2015, the daily renewable generation is above the 90th percentile and the daily demand is below the 10th percentile on only 52 occasions. All of these events are on weekend days (36 on Sundays) and 54% occur in either May or September.

The required system interventions can vary by the time of day and season. The worst case combination of high renewable generation from sun and wind coinciding with low demand can fall at any time of year, but has a bimodal nature. For winter, supply surplus is likely to come overnight, whereas during the summer surplus is most likely to fall at mid-day. This has implications for a significant body of current research exploring demand response and flexibility provision, not least the design of time of use tariffs.

The magnitude of the excess energy is highly dependent on the ratio of wind and solar capacity. This analysis therefore reinforces the merits of a blend of renewables and points to a 'sweet spot' mix of wind and solar. For Great Britain, the level of excess energy is at a minimum value for a blend of renewables capacity of 48% solar and 52% wind. In terms of system curtailment, the current system is therefore close to optimum mix and any future changes to this ratio could have significant implications. For example, as the capacity of wind continues to grow over the coming years, it creates an opportunity for the expansion of solar capacity to minimise the impact on the system. For a solar dominated system, the generation is limited to daylight hours predominantly in the summer months at which time the demand is relatively low and consequently high levels of curtailment would be required in these periods. For a wind dominated system, periods of excess energy are driven by wind generation overnight in winter and autumn months when the demand is low.

References

1. International Energy Outlook (2017), https://www.eia.gov/outlooks/ieo/). 14th September 2017.
2. Department for Business, Energy and Industrial Strategy (2017) Digest of UK Energy Statistics (DUKES) 2017 Main Report. https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2017-main-report
3. Department for Business, Energy and Industrial Strategy (2017) Energy Trends December 2017. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/669750/Energy_Trends_December_2017.pdf
4. Elexon (2018), BM Reports: Generation by fuel type. https://www.bmreports.com/bmrs/?q=generation/fueltype
5. Kubik, M. L., Coker, P. J., & Barlow, J. F. (2015). Increasing thermal plant flexibility in a high renewables power system. *Applied Energy*, *154*, 102–111. doi:10.1016/j.apenergy.2015.04.063

6. Bloomfield, H. C., Brayshaw, D. J., Shaffrey, L. C., Coker, P. J., & Thornton, H. E. (2016). Quantifying the increasing sensitivity of power systems to climate variability. doi:10.1088/1748-9326/11/12/124025
7. Jacobsen, H.K. and Schroder, S.T. (2012). Curtailment of renewable generation: Economic optimality and incentives. *Energy Policy*, 49, 663-675. http://dx.doi.org/10.1016/j.enpol.2012.07.004
8. Burke, D.J. and O'Malley, M. (2011). Factors Influencing Wind Energy Curtailment. IEEE Transactions on Sustainable Energy, 2 (2), 185-193. http://dx.doi.org/10.1109/TSTE.2011.2104981
9. McGarrigle, E.V., Deane, J.P. and Leahy, P.G. (2013). How much wind energy will be curtailed on the 2020 Irish power system? Renewable Energy, 55 pp 544-553. doi:10.1016/j.renene.2013.01.013
10. Ledesma, P., Arredondo, F. and Castronuovo, E.D. (2017). Optimal Curtailment of Non-Synchronous Renewable Generation on the Island of Tenerife Considering Steady State and Transient Stability Constraints. Energies, 10, 1926, doi:10.3390/en10111926
11. EIRGRID, Operational Constraints Update (2017) http://www.eirgridgroup.com/site-files/library/EirGrid/OperationalConstraintsUpdateVersion1_50_March_2017_Final.pdf
12. Flynn, D., Rather, Z., Ardal, A., D'Arco, S., Hansen, A.D., Cutululis, N.A., Sorensen, P., Estanquiero, A., Gomez, E., Meanemenlis.,Smith, C. and Y. Wang (2017). Technical Impacts of high penetration levels of wind power on power system stability. WIREs Energy Environ, doi: 10.1002/wene.216
13. Tielens, P. and Van Hertem, D. (2016). The relevance of inertia in power systems. Renewable and Sustainable Energy Reviews. Vol 55 pp 999-1009. http://dx.doi.org/10.1016/j.rser.2015.11.016
14. National Grid (2017). Product Roadmap: For Frequency Response and Reserve. http://nationalgridconnecting.com/product-roadmap-published/
15. National Grid (2016). System Operability Framework 2016. https://www.nationalgrid.com/uk/publications/system-operability-framework-sof
16. National Grid (2018). Future Energy Scenarios. http://fes.nationalgrid.com/fes-document/fes-2018/
17. Tuohy, A., & Malley, M. O. (2011). Pumped storage in systems with very high wind penetration Energy Policy, 39(4), 1965–1974. doi:10.1016/j.enpol.2011.01.026
18. Deane, J. P., Drayton, G., & Gallachóir, B. P. Ó. (2014). The impact of sub-hourly modelling in power systems with significant levels of renewable generation. Applied Energy, 113, 152–158. doi:10.1016/j.apenergy.2013.07.027
19. Macdonald, A. E., Clack, C. T. M., Alexander, A., Dunbar, A., Wilczak, J., & Xie, Y. (2016). Future cost-competitive electricity systems and their impact on US CO2 emissions. Nature Climate Change, Vol 6, pp 526-531. doi:10.1038/NCLIMATE2921
20. Jacobson, M. Z., Delucchi, M. A., Cameron, M. A., & Frew, B. A. (2015). Low-cost solution to the grid reliability problem with 100 % penetration of intermittent wind , water , and solar for all purposes. PNAS, 112(49), 15060–15065. doi:10.1073/pnas.1510028112
21. Cannon, D. J., Brayshaw, D. J., Methven, J., Coker, P. J., & Lenaghan, D. (2015). Using reanalysis data to quantify extreme wind power generation statistics : A 33 year case study in Great Britain. Renewable Energy, 75, 767–778. doi:10.1016/j.renene.2014.10.024
22. Drew, D., Cannon, D., Brayshaw, D., Barlow, J., & Coker, P. (2015). The Impact of Future Offshore Wind Farms on Wind Power Generation in Great Britain. Resources, 4(1), 155–171. doi:10.3390/resources4010155

23. Pfenninger, S., & Staffell, I. (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy, 114, 1251–1265. doi:10.1016/j.energy.2016.08.060
24. Bett, P. E., & Thornton, H. E. (2016). The climatological relationships between wind and solar energy supply in Britain. Renewable Energy, 87, 96–110. doi:10.1016/j.renene.2015.10.006
25. Staffell, I., & Pfenninger, S. (2018). The increasing impact of weather on electricity supply and demand. Energy, 145, 65–78. doi:10.1016/j.energy.2017.12.051
26. 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 Great Britain. Environmental Research Letters, 11 (11). 114015. ISSN 1748-9326 doi: https://doi.org/10.1088/1748-9326/11/11/114015
27. Drew, D, Bloomfield, H, Coker, P, Barlow, J Brayshaw, D (2019): MERRA derived hourly time series of GB-aggregated wind power, solar power and demand. University of Reading. Dataset. http://dx.doi.org/10.17864/1947.191
28. Boilley, A., & Wald, L. (2015). Comparison between meteorological re-analyses from ERA-Interim and MERRA and measurements of daily solar irradiation at surface. Renewable Energy, 75, 135–143. doi:10.1016/j.renene.2014.09.042
29. Department for Business, Energy and Industrial Strategy (2017). Installed Capacity (kW) of domestic photovoltaic installations by Local Authority. https://www.gov.uk/government/statistical-data-sets/sub-regional-feed-in-tariffs-confirmed-on-the-cfr-statistics

- Derived long term time series of wind, solar and demand
- Determined hourly proportion of demand from renewables for a 36-year period
- Sunny, windy weekend days have highest penetration of renewables
- Derived volume of curtailment for range of penetration limits
- Volume of curtailment varies with blend of wind and solar capacity