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The climatological relationships between wind and solar energy supply in Britain

Philip E. Bett*, Hazel E. Thornton**

Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, United Kingdom

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ABSTRACT

We use reanalysis data to investigate the daily co-variability of wind and solar irradiance in Britain, and its implications for renewable energy supply balancing. The joint distribution of daily-mean wind speeds and irradiances shows that irradiance has a much stronger seasonal cycle than wind, due to the rotational tilt of the Earth. Irradiance is weakly anticorrelated with wind speed throughout the year ($-0.4 \lesssim \rho \lesssim -0.2$): there is a weak tendency for windy days to be cloudier. This is particularly true in Atlantic-facing regions (western Scotland, south-west England). The east coast of Britain has the weakest anticorrelation, particularly in winter, primarily associated with a relative increase in the frequency of clear-but-windy days. We also consider the variability in total power output from onshore wind turbines and solar photovoltaic panels. In all months, daily variability in total power is always reduced by incorporating solar capacity. The scenario with the least seasonal variability is approximately 70%-solar to 30%-wind. This work emphasises the importance of considering the full distribution of daily behaviour rather than relying on long-term average relationships or correlations. In particular, the anticorrelation between wind and solar power in Britain cannot solely be relied upon to produce a well-balanced energy supply.

1. Introduction

It is well known that the British Isles are in an ideal geographic situation for exploiting wind energy, and promoting wind energy has been central to UK government policy on low-carbon energy (e.g. the original version of the Renewable Energy Roadmap, [13]). However, electricity generation from solar photovoltaic panels (hereafter, solar PV[1]) has seen huge growth in recent years, driven largely by global economic factors [3,9]. Reductions in the cost of PV panels have helped to make large-scale use of solar PV in the UK financially viable, resulting in corresponding adjustments to government policy (e.g. the update to the Renewable Energy Roadmap [15], and the Solar PV strategy [16,17]).

Both wind and solar power output are highly variable [2,47,51]. This covers weather variations on timescales of minutes and hours, through to days and seasons, and even to long-period climate variations occurring over years and decades, linked to climate indices such as the North Atlantic Oscillation (NAO, [12,31,44]). However, while the variability of both is ultimately driven by the rotation of the Earth under the Sun, wind speed and irradiance exhibit different variability characteristics. It has become increasingly important therefore to understand the relationship between energy supplied by wind and by solar PV, and the extent to which variability in one source can help to balance out the variability in the other.[2] This has important practical implications in terms of the need for energy storage and/or back-up capacity (e.g. from pumped storage, gas or nuclear power stations), and for the operational requirements of electricity networks.

There have been many different studies looking into these issues, with a variety of different aims, regions of interest and methodological approaches. Coker et al. [11] focused on a single area in the Bristol Channel (south-west Britain), using observational records for the year 2006. They demonstrated a range of different statistical approaches to assessing the variability of the wind, solar and tidal current energy resources in that region, on timescales of half-hours to the full year's seasonal cycle. Santos-Alamillos et al. [42] used canonical correlation

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* Corresponding author.
** Corresponding author.
E-mail address: philip.bett@metoffice.gov.uk (P.E. Bett).

[1] Note that we focus exclusively on electrical energy generation in this paper, and in Britain, photovoltaic panels are by far the dominant mode of electricity generation that uses solar energy directly.

[2] Prior to the recent solar energy boom, work on the co-variability of renewable energy sources in the UK had focused on the relationship between wind and marine energy sources (wave and tidal power, e.g. Ref. [45]). While this is now less of an immediate priority, it may become an important issue again in future.

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analysis to find the optimal spatial distribution of wind and solar farms across the southern Iberian Peninsula to minimise the resulting net variability. However, Monforti et al. [39] found that the specific locations of generation sites made very little difference to balancing between hypothetical wind and solar supply in Italy. Heide et al. [27,26] modelled the energy storage and balancing requirements for Europe under a hypothetical high-renewable scenario, balancing wind and solar supply against demand using data spanning 2000–2007. While their modelling is more detailed, and makes more assumptions than the work we present here, some of their conclusions are very general and important: the optimal balance of wind and solar supply to match demand (over Europe, circa 2007) requires large amounts of storage and/or balancing supply. They show that this can be reduced by allowing excess supply (i.e. frequent instances of supply exceeding demand), and the amounts involved affect the optimal mix between wind and solar power. Whether one considers hourly or daily variability also has a strong impact on the relationships. Other studies have also looked into finding the ‘optimal’ combination of wind and solar power, for different regions and using data spanning different periods [36,46,49], and studies generally find that incorporating both renewable sources acts to reduce the net variability in power supply, reducing the need for reserves (e.g. Refs. [24,29,35] in addition to those already mentioned; see also the recent review of Widén et al. [50]).

Our present study differs from these in several key respects. Firstly, we are interested primarily in the wind–solar co-variability across Great Britain (GB) as a whole; many of the studies above use data from a limited number of specific sites. We effectively assume that electricity networks will be able to redistribute power sufficiently to work around local imbalances. Secondly, we are looking to avoid detailed modelling of the GB power system itself, such as details of the locations of wind and solar farms, their capacities, network connectivity, available storage etc. This information is likely to change significantly from year to year, in terms of total capacity, its partitioning between different energy sources, its geographic distribution etc., and this could have a significant impact [22], limiting the applicability of our results. Our study intends to focus on more general climatological features, based on historical data from recent decades.

Accordingly, we are also not considering electricity demand. Ultimately, the importance of balancing wind and solar power lies in whether or not they can together help match demand – i.e. it doesn't matter if wind power is low, if demand is also low at the time. However, modelling demand, including separating its socio-economic and meteorological dependencies, requires significant attention in itself, and is beyond the scope of this paper. Furthermore, the demand profile of Britain is likely to be significantly different in the future (e.g. Ref. [23]), which adds extra uncertainties to such work. It is useful to know what the relative behaviour is between potential wind and solar power output, as this forms the general, theoretical basis for subsequent practical applications that use particular demand/generation scenarios.

Finally, unlike most of the studies referenced above, we are focussing on the impacts of *climate* variability on wind and solar energy supply: we consider monthly and seasonal variability based on many years of daily data. We are not considering either sub-daily or interannual/decadal variability. Both are important, for example for understanding the frequency of ramping events (e.g. Ref. [10]), or the likely output over the lifetime of a wind farm [5,6,32] or solar installation [1,12], but are outside the scope of this paper. In the present study we are interested in understanding the distribution of possible wind–irradiance states, and treat different years as samples from an underlying climatological distribution.

This paper proceeds as follows. In Section 2 we describe the data we have used, and our analysis techniques. Our results on the joint distributions of wind and irradiance are discussed in Section 3. We discuss the impact of the wind–irradiance distribution on the resulting total power variability for different scenarios in Section 4. Our conclusions are presented in Section 5.

2. Data and methods

This study uses the ECMWF[3] Re-Analysis Interim data set (ERA-Interim), which is described in full in Dee et al. [19] and Berrisford et al. [4]. We have obtained ERA-Interim data covering 1979–2013, at 0.75° spatial resolution.

Despite being based on assimilations of vast amounts of observational data, from ground stations as well as satellites, the low spatial resolution of the ERA-Interim data means that it should be treated with caution when comparing its results to observations. We use ERA-Interim because its wind speeds, irradiances, temperatures etc. are produced from the same physical model, constrained by observations. This means that they are physically consistent at any given time step, and at a consistent spatial scale. This is a distinct advantage over using a mixture of data sources, such as reanalysis in conjunction with satellite-based or station-based observations. We reiterate, the goal is to assess the co-variability of wind and solar resources at the GB scale, *not* to produce a detailed, accurate description of the available resource.

A recent study by Boilley and Wald [7] showed the deficiencies in using reanalysis data for estimates of irradiance, compared to satellite-based data. They found that reanalyses tend to have too many clear-sky days compared to observations, although in the particular case of ERA-Interim this is countered somewhat by also having many cloudy days that were observed to be clear. A substantial amount of the true variability in irradiance *at a site* is not captured in reanalysis data. The difficulty in our case, motivating our decision not to use satellite data, is in finding comparable high quality wind speed data that we can use in our co-variability assessment. Kubik et al. [34] assessed the use of reanalysis data for regional wind assessments, and found that its benefits, such as its continuous nature over a long time period, outweighed the disadvantages from low resolution, when used with care.

Using ERA-Interim, we have taken the daily (24 h) means of the 6-hourly wind speed fields at model level 58, which corresponds to a height of roughly 60 m above ground level. We denote these wind speeds by U.

Daily-mean downwelling shortwave irradiance[4] at the surface[5] is not directly available from the ERA-Interim data archive, and has to be calculated from the 3-hourly forecast fields for accumulated irradiation. The resulting fields are daily-mean downwelling total irradiances at the surface, for a horizontal plane. Since ERA-Interim does not track the direct and diffuse radiation components separately, we are not able to calculate the irradiance falling on a tilted surface. Because total irradiance (direct + diffuse) is often termed ‘global’ irradiance, we denote it by G.

Much of the local variability in solar irradiance is directly due to the tilt of the Earth's rotational axis with respect to its orbit, known as its obliquity.[6] This causes variation in both the total hours of daylight and the overall intensity of the incident radiation (the amount per unit area). These ‘astronomical’ factors have two key

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[3] The European Centre for Medium-range Weather Forecasting.

[4] Irradiance is the radiative energy flowing through a unit area per unit time; cf. irradiation or insolation, which is the total radiative energy per unit area, integrated over a given time.

[5] For brevity, all irradiance/irradiation fields in this paper should be interpreted as referring to downwelling shortwave radiation at the surface, unless otherwise noted.

[6] The seasonal cycle in wind speeds can be traced back to the same factors of course, but much less directly.