RENEWABLE AND SUSTAINABLE ENERGY REVIEWS
Research Article

Meteorological conditions leading to extreme low variable renewable energy production and extreme high energy shortfall

SUPPORTING INFORMATION

A | ENERGY MODEL ADDITIONAL FIGURES

Section 3 in the main text provides a full description of the energy model developed to transform meteorological data into energy variables. Here we provide some additional figures (Figs. S1, S2) that show the conceptual model in more detail. Furthermore we include a figure showing the 'uniform distribution' of installed capacity that is used to analyse the sensitivity of our results to the projected spatial distribution of installed wind turbines and solar panels (Fig. S3).

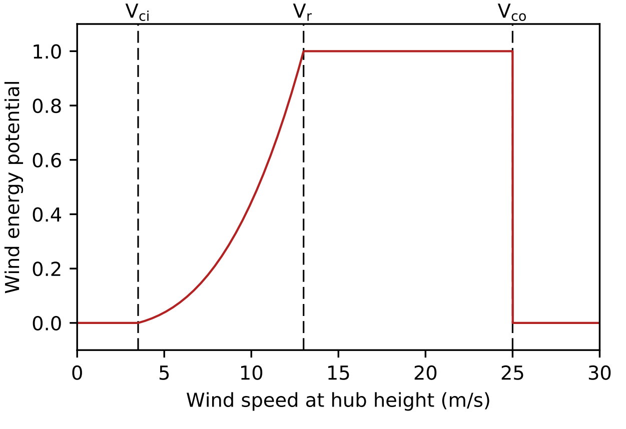

FIGURE S1 Wind energy potential (no units, red line) as a function of wind speed at hub height (m/s), following equation 4 of the main text. Dashed vertical lines show the cut-in wind speed (V_{ci}), rated wind speed (V_r) and cut-out wind speed (V_{co}).

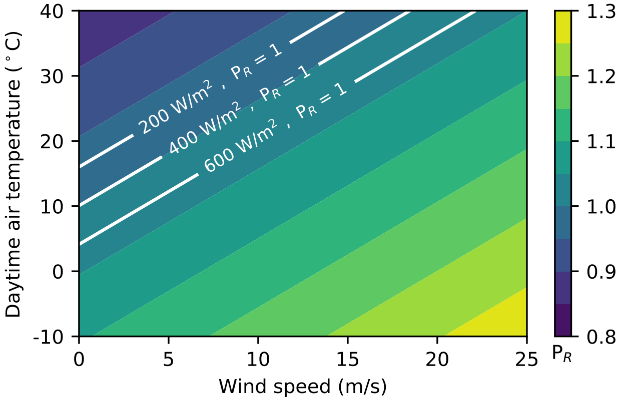

FIGURE S2 Performance ratio of a modelled solar cell (no units, shaded colours) as a function of daytime air temperature (°C) and wind speed (m/s) assuming incoming solar radiation to be 400 W/m^2 following equations 6 and 7 of the main text. White lines show $P_R = 1$ for different values of incoming solar radiation.

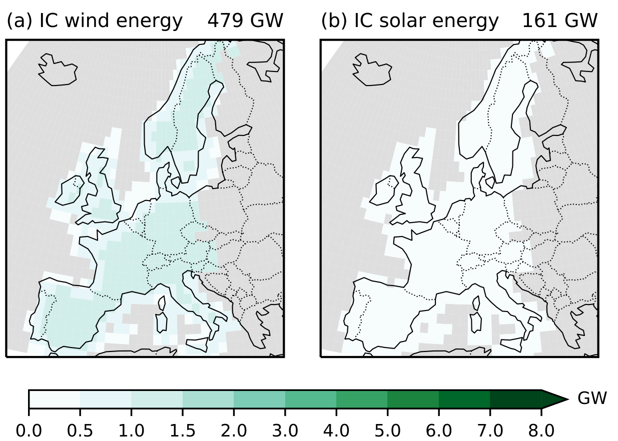

FIGURE S3 As Figure 3 of the main text, but here for the uniform distribution. Note the total installed capacity is equal to that of the projected distribution.

B | STATISTICS OF MODELLED ENERGY VARIABLES

In Sections 4.1 and 5.1 of the main text we compare mean values and variability of the EC-Earth simulations and ERA-interim data. For completeness and ease of comparison we include tables noting the same values here (Tables S1,S2). Table S3 shows the same for the HadGEM2-ES present-day simulations, referred to in Section 6.1 of the main text. Note DJF was chosen to represent the winter season (December-January-February), JJA represents the summer season (June-July-August).

TABLE S1 Annual and seasonal mean statistics of modelled energy variables (TWh/day or %), based on the EC-Earth present-day large-ensemble experiment. Mean and standard deviation (st.dev.) are shown, and the 1-in-10 year event selection threshold for the two energy impact variables considered.

	units	mean			st.dev.			1-in-10 yr threshold
		annual	DJF	JJA	annual	DJF	JJA	annual
Wind energy production	TWh/day	2.1	3.9	1.2	1.2	1.2	0.7	
Solar energy production	TWh/day	0.7	0.3	1.0	0.3	0.1	0.1	
Total energy production	TWh/day	2.7	3.3	2.2	1.1	1.2	0.7	0.6
Energy demand	TWh/day	7.9	8.5	7.2	0.5	0.2	0.1	
Renewable share	%	35	39	31	13	15	10	
Energy shortfall	TWh/day	5.1	5.2	5.0	1.1	1.3	0.7	8.0

TABLE S2 As Table S1 but here for ERA-interim data (1979-2017).

	units	mean			st.dev.			1-in-10 yr threshold
		annual	DJF	JJA	annual	DJF	JJA	annual
Wind energy production	TWh/day	2.6	3.5	1.6	1.4	1.5	0.9	
Solar energy production	TWh/day	0.7	0.3	1.0	0.3	0.1	0.1	
Total energy production	TWh/day	3.2	3.8	2.6	1.3	1.5	0.9	0.8
Energy demand	TWh/day	7.7	8.5	7.2	0.6	0.3	0.0	
Renewable share	%	42	45	36	16	19	12	
Energy shortfall	TWh/day	4.5	4.7	4.6	1.3	1.7	0.9	7.9

TABLE S3 As Table S1 but here for the HadGEM2-ES present-day large ensemble experiment.

	units	mean			st.dev.			1-in-10 yr threshold
		annual	DJF	JJA	annual	DJF	JJA	annual
Wind energy production	TWh/day	1.3	2.1	0.6	1.0	1.0	0.4	
Solar energy production	TWh/day	0.7	0.3	1.1	0.3	0.1	0.1	
Total energy production	TWh/day	2.0	2.4	1.6	0.8	1.0	0.4	0.5
Energy demand	TWh/day	7.8	8.5	7.3	0.6	0.3	0.1	
Renewable share	%	25	28	22	10	13	5	
Energy shortfall	TWh/day	5.8	6.1	5.6	0.9	1.2	0.4	8.4

C | COMPARISON ERA-INTERIM TO MODEL RESULTS

The results in sections 4 and 5 of the main text are mostly based on the EC-Earth present-day large ensemble experiment. The climate model experiment provide us with 2000 years of daily data and therefore with the opportunity to sample and investigate extreme events. The ERA-interim reanalysis product covers the period 1979-2017, i.e. 39 years, which is too short to adequately sample extreme events. The aim of this section is to show that the model results are in line with what can be said based on the limited ERA-interim record.

Figs. S4 and S5 show meteorological composite mean conditions for 1-in-10 year low energy production events and high energy shortfall events in the ERA-interim data. Note that these composites are based on four events only, and are therefore more sensitive to single event outliers than the model results are. Despite this limitation, the meteorological conditions from the ERA-interim composites are close to those from the model results (Figs. 6 and 9 in the main text for EC-Earth, Figure 12 in the main text for HadGEM2-ES). The anomalies for ERA-interim are larger than those for EC-Earth, most notably for incoming solar radiation and 2 m temperature. This is in part the result of averaging over fewer events, but might also be related to model biases.

To verify that the simulated extreme events from EC-Earth and HadGEM2-ES are comparable to those in the ERA-interim dataset, we have developed three metrics to compare the events:

- **Surface pressure** The spatial correlation of the surface pressure pattern to that of the multi-model mean composite (EC-Earth and HadGEM2-ES, 400 event mean). Region taken into consideration: 35-65°N, 10°W-25°E.
- **10 m wind speed** The mean 10 m wind speed anomaly over the southern North Sea region (50-60°N, 0-10°E).
- **2 m temperature** The population weighted 2 m air temperature over the entire region considered in the study.

For each selected low renewable energy production event and each high energy shortfall event in all datasets (200 for EC-Earth, 200 for HadGEM2-ES, 4 for ERA-interim), we have computed the above metrics. Figs. S6 and S7 show the modelled distributions and the location of the four ERA-interim events within these distributions.

All ERA-interim events, low renewable energy production and high energy shortfall, fall within the simulated distributions of both the EC-Earth and HadGEM2-ES models, for all metrics. This provides us with confidence that the simulated high-impact events are realistic events. There are differences between the two simulated distributions, on average the EC-Earth events exhibit stronger 10 m wind speed anomalies in the southern North Sea than HadGEM2-ES events, and EC-Earth high shortfall events are on average warmer than HadGEM2-ES high shortfall events. Based on the four ERA-interim events it is not possible to say which simulated distribution of extreme events is closer to the distribution of extreme events in the real world.

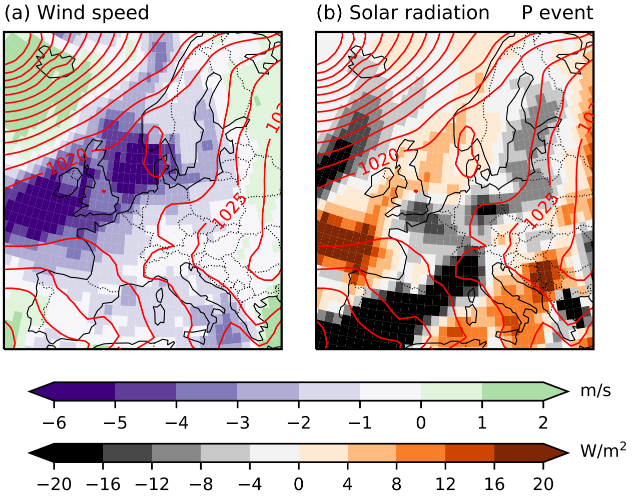

FIGURE S4 Reproduction of Fig. 6d,h and 12a,b of the main text, but here based on data from ERA-interim.

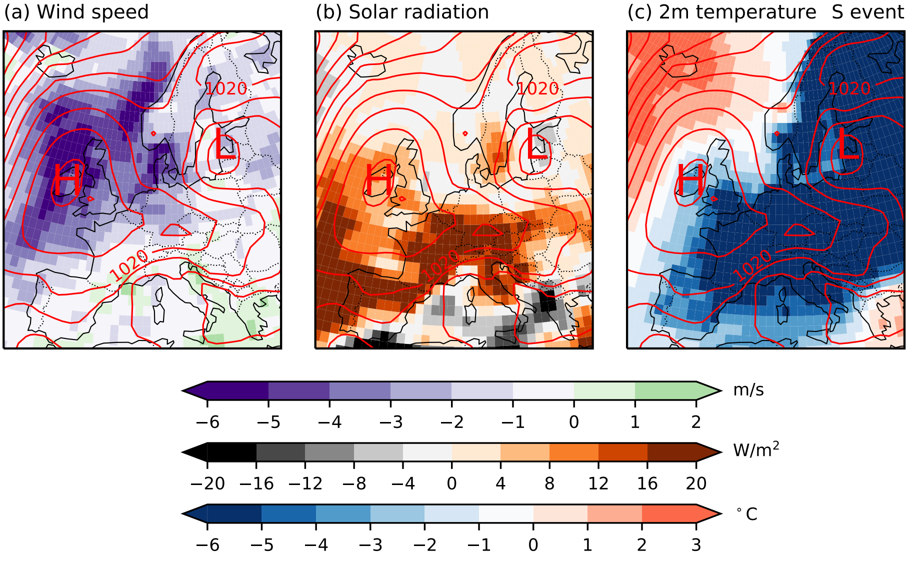

FIGURE S5 Reproduction of Fig. 9d,h,l and 12d,e of the main text, but here based on data from ERA-interim.

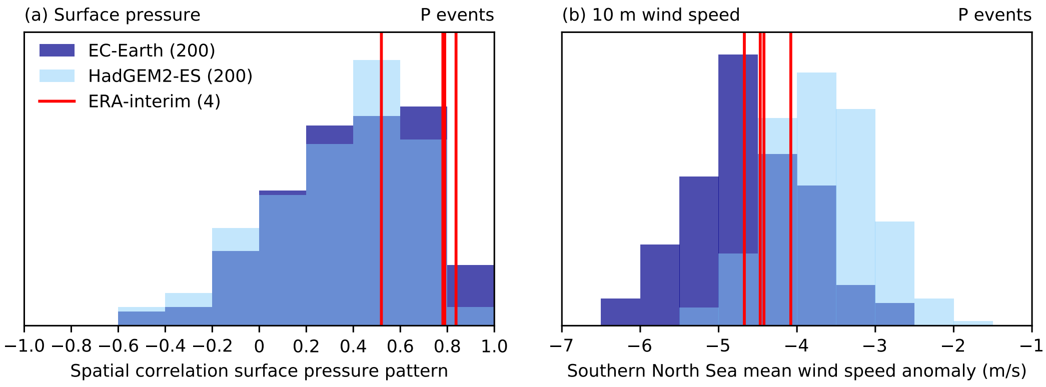

FIGURE S6 Histograms for the distribution of (a) the surface pressure metric (no units), and (b) the 10 m wind speed metric (m/s) for low renewable energy production events. Dark blue shows the EC-Earth distribution, light blue the HadGEM2-ES distribution, red lines the ERA-interim events.

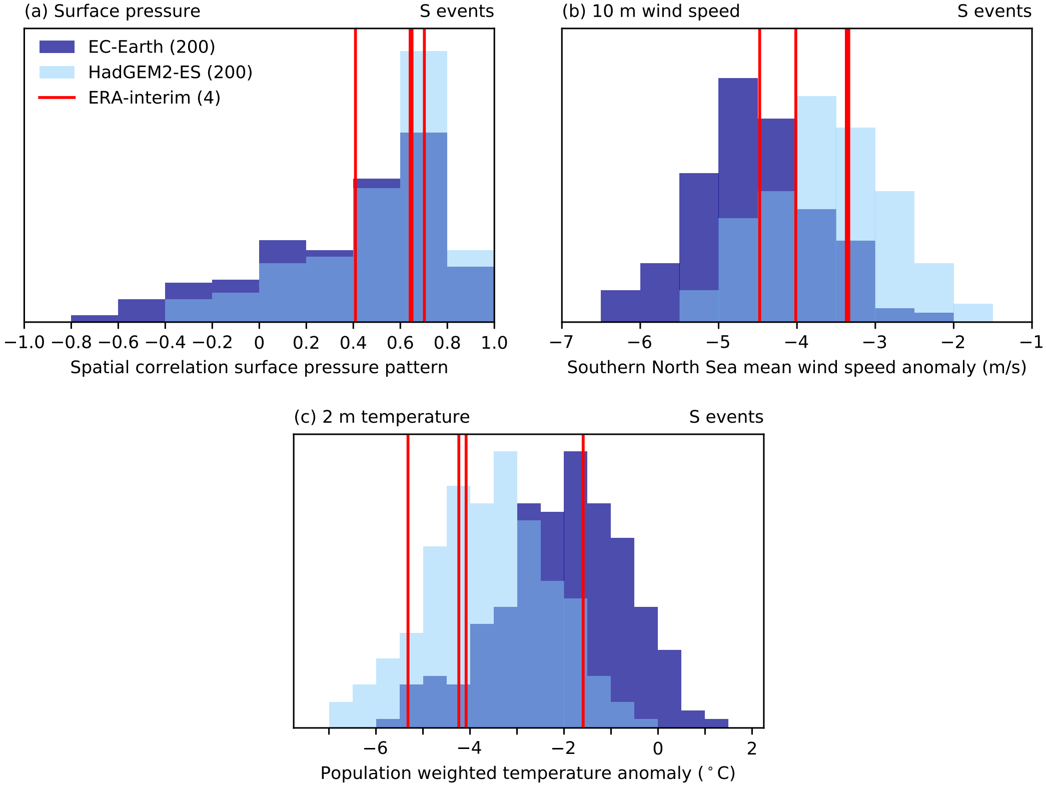

FIGURE S7 (a,b) as Fig. S6, but here for the distributions of all three metrics for high energy shortfall events. (c) shows the histogram of the distribution of 2 m temperature (°C).