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On the Link Between Weather Regimes and Energy Shortfall During Winter for 28 European Countries

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ABSTRACT

Increasing the proportion of energy generation from renewables is a necessary step towards reducing greenhouse gas emissions. However, renewable energy sources such as wind and solar are highly weather sensitive, leading to a challenge when balancing energy demand and renewable energy production. Identifying periods of high shortfall, here defined as when electricity demand substantially exceeds renewable production, and understanding how these periods are affected by weather is therefore critical. We use a previously constructed energy dataset derived from reanalysis data for a fixed electricity system to analyse the link between weather regimes and periods of high shortfall during the winter for 28 European countries. Building on previous work and following similar studies, we provide both a subcontinental and country-specific perspective. For each country, we identify days with critical energy conditions, specifically high-energy demand, low wind and solar generation, and high-energy shortfall. We show that high shortfall is more driven by demand than by production in countries with colder climates or less installed wind capacity, and is more driven by production than by demand in countries with warmer climates or more installed wind capacity. Of the six weather regimes considered here, only a subset is found to favour the occurrence of high shortfall days. This subset affects much of Europe, causing simultaneous shortfall days across multiple countries. Furthermore, if multiple countries experience shortfall days, neighbouring countries are more likely to experience shortfall days. Motivated by this result, we examine the hypothetical impact the coldest European winter of the 20th century, 1962/1963, would have had on the present-day energy system. We found that persistent blocking conditions associated with that winter, if they occurred today, would lead to higher demand and shortfall across Europe during most of the winter and would be extreme in this respect compared to other winters.

1 | Introduction

A transition towards renewable energies is one of the main objectives of the European Green Deal to limit global warming (European Commission 2019). While weather conditions so far predominantly affected the energy network through influencing energy demand, renewable energy sources such as wind and solar generation are intrinsically dependent on weather (Van der Wiel, Bloomfield, et al. 2019; Bloomfield et al. 2016). Thus, with the increase in the proportion of renewable generation, the energy network is becoming more weather-dependent, implying the challenging task of balancing variable energy sources with variable energy demand.

The current energy network in Europe is robust, making blackouts very unlikely. This is partly thanks to the European energy system being highly interconnected between individual, national entities. The European Network of Transmission System Operators for Electricity (ENTSO-E) has 40 member companies from 36 different countries (Member companies n.d.). The member companies are Transmission System Operators (TSO) that are responsible for most of the transmission of electricity on national high-voltage networks. They are targeted to guarantee the safe operation of the system, and in many countries (including France, Germany, United Kingdom), they are also in charge of the development of the grid infrastructure. The TSOs that are part of ENTSO-E are split into synchronous areas (ENTSO-e 2009). These synchronous areas are groups of countries with connected energy networks, with the benefits being grouping of generation, common energy reserves and mutual help in case of a disturbance.

However, even with such a robust network, there are consequences to periods of high demand and low renewable generation. If the supply of energy is limited, other energy sources are required which can be more expensive and/or more polluting (e.g., liquefied natural gas, energy imports, gas-fired power stations), leading to more volatile prices (Lawson and Voce 2023; Beating the European Energy Crisis 2022). These situations can be further amplified by political tension such as with the onset of the Ukraine war, which rekindled the fear of blackouts (Kingsley 2022; Martínez-García et al. 2023).

Recent studies have addressed the particular challenge of periods with high demand and low renewable generation, variously referred to as energy shortfall (Van der Wiel, Bloomfield, et al. 2019), energy compound events (Otero et al. 2022), peak demand-net-renewables (Bloomfield et al. 2020a), residual load (van der Wiel, Stoop, et al. 2019), energy drought (Raynaud et al. 2018), and Dunkelflauten (Mockert et al. 2023). Understanding these periods of high demand and low renewable generation, hereafter called energy shortfall, is critical to the energy transition as any gap in energy generation will need to be covered by either using more polluting energy sources, importing energy from neighbouring countries, or using energy storage. These alternatives can harm the transition by either emitting pollution or affecting energy prices for consumers.

Among recent studies, some have investigated the influence of weather regimes on renewable generation (Grams et al. 2017; Thornton et al. 2017), including energy shortfall events (Mockert et al. 2023; van der Wiel, Stoop, et al. 2019). European weather regimes are large-scale atmospheric patterns defined over the North Atlantic, representing most of the low-frequency variability (Michelangeli et al. 1995; Straus et al. 2007), meaning that they go beyond the day-to-day weather timescale (Hannachi et al. 2017). Weather regimes modulate surface weather (Cassou et al. 2004; Ferranti et al. 2018) and are associated with high-impact extreme events such as heatwaves and cold spells (Cassou et al. 2005; Matsueda 2011). Weather regimes are used in the energy sector to characterise the potential for different energy scenarios (Grams et al. 2017) and also to provide forecasts at longer time ranges (Bloomfield et al. 2021). Their influence on energy-related variables (i.e., temperature, wind, solar radiation) motivates studies on the use of weather regimes to inform the deployment of wind farms (Grams et al. 2017), to understand the sensitivity of a renewable energy generation system (van der Wiel, Stoop, et al. 2019), or to forecast renewable generation (Bloomfield et al. 2021).

In the context of anthropogenic climate change, the evolution of weather regimes will affect their influence on surface parameters and extremes (Herrera-Lormendez et al. 2023). However, projected changes of atmospheric circulation and weather regimes, be it in frequency, persistence or pattern, are more uncertain than temperature projections (Shepherd 2014). Therefore, having a good understanding of the current impact of such regimes on the energy system is crucial for assessing future impacts.

The aim of the present study is to understand the relationship between weather regimes and energy (specifically, electricity) shortfall across 28 different European countries and regions. Ideally, this might be done with an ensemble of possible winters (produced by a climate model) for a given year, with the electricity system at that time. However, that would depend on the fidelity of the climate model. An alternative is to use the observed record, as represented in reanalysis (representing the best estimate of the actual multivariate atmospheric state; Dee et al. 2011), as an indication of what is possible, applied to a fixed energy system. Such a counterfactual calculation is available in the energy dataset of Bloomfield et al. (2020b), for 2017 energy-system conditions. Although the European energy system has evolved since 2017, this dataset allows for the investigation of the impact of weather variability on energy shortfall for a contemporary European energy system, without the confounding effect of changes in the energy system. It is thus suitable for our purpose here.

As previous studies have looked at Europe as a whole (van der Wiel, Bloomfield, et al. 2019; van der Wiel, Stoop, et al. 2019) or at individual countries (Bloomfield et al. 2018), we aim here to look at the entirety of the 28 European countries available in this dataset from a subcontinental perspective and highlight both their commonalities and their differences. The characteristics of extreme energy days and longer periods of extreme energy conditions are investigated, including an exploratory analysis of their long-term trends. We quantify the relative influence of weather regimes on energy shortfall on individual countries. Further on, we examine periods of simultaneous high shortfall across countries that are part of the Regional Security Coordinators (Power regions 2022) and the rest of Europe. Finally, the energy effects of an extremely cold and persistent winter are assessed through a case study of the coldest winter in Europe of the 20th century (the winter of 1962/1963), if it occurred under current (c. 2017) conditions.

2 | Data and Methods

The ERA5 reanalysis dataset (Hersbach et al. 2020) from the European Centre for Medium-Range Weather Forecasts (ECMWF) is used to characterise the meteorological conditions. From ERA5, the daily mean 2-m temperature (2mT), geopotential at 500 hPa (Z500), zonal (u10m) and meridional wind components (v10m) at 10-m, and incoming solar radiation (ISR; top-of-atmosphere net short-wave radiation flux) are used. The dataset covers the period 1979–2022 for the extended winter season (October to April included) from 20 N to 80 N and 90 W to 60 E at 1° horizontal resolution. From the wind components, the horizontal wind at 10-m (W10m) is computed:

$$W10\text{m} = \sqrt{u10\text{m}^2 + v10\text{m}^2}$$

From the daily mean values of all variables, daily anomalies are computed by subtracting the climatological values. The latter is estimated by sampling over a running window of 5 days, meaning that the climatology for a given day d in the year includes all days from d−2 to d + 2 of the years from 1979 to 2022.

Similarly, to the ERA5 data, the extended winter months (October to April included) are included for the energy dataset from Bloomfield et al. (2020b). This dataset contains energy demand (in megawatts, MW), as well as the capacity factor (CF) of both wind and solar data, which have been derived from ERA5 at hourly resolution. This dataset has the benefit of covering a long period from 1979 to 2019 for 28 different European countries (shown in Figure 5). For the calculation of energy variables, human factors such as energy infrastructure and the socio-economic conditions (e.g., demography, behaviour) are set to 2017 conditions across the entire period. This allows us to interpret the variability in energy supply and demand as only weather-driven. In particular, it allows us to sample the influence of weather and weather regimes on the current (c. 2017) infrastructure across a long period, to provide a larger sample size of weather variability.

The energy demand in Bloomfield et al. (2020b) is modelled using the population-weighted 2mT, thereby identifying periods where the population is likely to use heating (Heating Degree Days: HDD) or air conditioning (Cooling Degree Days: CDD). To identify the sensitivity of each country's energy demand to HDD and CDD, a multiple linear regression model using HDD and CDD is trained on observed national aggregated daily total demand (ENTSO 2019) for the years 2016 and 2017 and evaluated on 2018 data. Two energy demand datasets are available, one including a weekly cycle that takes into account that demand is higher during weekdays than weekend days, and another where each day is considered a Monday. In this study, only the dataset setting each day as a Monday is used. Although this renders the analysis less realistic, it allows for variations in energy to be driven by variations in meteorological conditions only, without the confounding influence of variations in socio-economic conditions and/or network constraints. Thus, as with the year-to-year variations, it increases the sample size of weather variability available for this study.

The wind CF in Bloomfield et al. (2020b) is estimated using horizontal wind at 100 m, as the wind turbines' hub height is assumed to be at 100 m. Additionally, the location of wind farms has been extracted from thewindpower.net by Bloomfield et al. (2020a) and is taken from the year 2017. Solar CF is estimated using incoming solar radiation and 2mT as temperature influences the efficiency of photovoltaic cells (e.g., reduced efficiency above 25°C). However, the distribution of solar photovoltaic capacity is assumed to be uniform, as reliable information is not available as it is for wind farms. For a more comprehensive explanation of the model used to derive the energy data, we refer to the supplementary material of Bloomfield et al. (2020a).

For better comparison with the daily meteorological data, the energy data are changed to daily values. For energy demand, the hourly demand is summed over the 24 h of each day. The CF represents the ratio of generated wind or solar energy to the installed capacity. Therefore, to get the daily renewable generation data, the CF is averaged for each day and multiplied by the installed capacity of the respective energy source times 24 h in a day. The installed capacity is taken from the ENTSO-E transparency platform for the year 2022. The year 2022 is chosen as installed capacities for wind and solar are reported for all countries from this year onwards. Shortfall is computed by removing the daily wind and solar generation (both in MW) from the daily demand and is also given in MW.

As mentioned in the Introduction, TSOs are part of synchronous areas. In addition, countries are grouped into Regional Security Coordinators (RSC; Power regions 2022). RSCs support TSOs through planning and recommendations, and help with coordination between TSOs that are part of the same RSC. The RSCs have been created to also address the diversification of energy sources, in particular the uptake of renewable energy sources. In this study, the RSCs are used to investigate the possibility of high shortfall over multiple countries of one RSC and the impact on neighbouring countries. The RSCs considered here are COoRdination of Electricity System Operators (CORESO), TSCNET Services GmbH (TSCNET), Nordic RSC, Baltic RSC, and Southeast Electricity Network Coordination Center (SEleNe CC). Only the Security Coordination Centre (SCC) RSC is not considered as data for only one of the countries (Montenegro) is available from the dataset used here.

2.1 | Energy Days Definition

Shortfall is defined as the difference between energy demand and renewable energy generation, also known as residual load (van der Wiel, Bloomfield, et al. 2019; van der Wiel, Stoop, et al. 2019). It is important to note that while this shortfall is usually positive, meaning demand is higher than renewable generation, it can also be negative if renewable generation exceeds energy demand and more. This can happen for countries with very high renewable capacity, such as Denmark and Germany.

We here focus on days with extreme energy conditions, which we call energy days. These are defined as days when a particular energy index goes above or below a percentile threshold, where the percentile is sampled from the distribution over the studied period. We consider four different cases of energy days: (1) demand days, when energy demand is above the 90th percentile; (2) wind drought days, when wind CF is below the 10th percentile; (3) solar drought days, when solar CF is below the 10th percentile; and (4) shortfall days, when energy shortfall is above the 90th percentile. The corresponding extreme energy events are treated as a series of consecutive energy days. We choose these percentiles in order to have sufficiently large sample sizes to enable a robust statistical analysis, checking the sensitivity to percentile choice in a few cases.

To discuss the effects of persistence, brief energy events are defined as those lasting 4 days or less, while long energy events are defined as those lasting 5 days or more. As a check of robustness, the analysis was also performed, defining brief energy events as lasting 3 days or less and long events as lasting 5 days or more, disregarding 4-day events (so as to create a clear distinction between brief and long events). The results are very similar; therefore, 4-day events are included in the brief events, which allows not to lose any data.

To highlight the effect of very persistent weather regimes, we analyse the extremely cold winter of 1962–1963 (Sippel et al. 2024). The winter of 1962–1963 is known as the coldest European winter of the 20th century (Hirschi and Sinha 2007). In the United Kingdom, snow fell the week after Christmas and stayed for most of the winter. Large bodies of water such as the Rhine River and Lake Constance were frozen. Temperatures dropped to −26°C in Vichy in France and below −40°C in Warsaw (Hiver 1962–63 n.d.). This resulted in severe impacts on human health, energy demand and the environment (Eichler 1971). This winter was synoptically characterised by a strong and persistent NAO− (Hirschi and Sinha 2007; Greatbatch et al. 2015). As the energy dataset used here does not cover this winter, we use another available dataset covering the period from 1950 to 2020 (Bloomfield and Brayshaw 2021). This latter dataset uses a similar methodology to the one used here except for the demographic conditions. However, the location of wind farms is taken from 2020 rather than 2017, and the installed solar capacity is not spread homogeneously as in Bloomfield et al. (2020b), but based on actual solar farm locations extracted from Dunnett et al. (2020) and Stowell et al. (2020). Moreover, the wind and solar CF are provided for only 12 countries compared to the 28, and demand is not provided. However, the population-weighted temperature for each country is available. Using the model parameters from the previous dataset and the demand model instruction provided in the supplementary documents of Bloomfield et al. (2020a), the demand data are computed. For consistency, the energy days are computed using the percentile values from this dataset covering the period 1950–2020. These percentile values are very similar, within 1%, compared to the shorter dataset from Bloomfield et al. (2020b). Further investigation also showed that the results obtained in section 3a are essentially the same with only minor differences in amplitude.

2.2 | Weather Regime Computation

We compute weather regimes applying the k-means clustering algorithm on Z500 anomaly data (Michelangeli et al. 1995; Hannachi et al. 2017; Falkena et al. 2020). Following the recommendations of Falkena et al. (2020), the clustering is performed on the full anomaly field instead of performing a dimensionality reduction first. The k-means algorithm requires setting the number k of clusters and iteratively identifies the optimal partition of the data. The most used weather regime classification uses four regimes (Michelangeli et al. 1995; Ferranti et al. 2015) but in recent years, new classifications have been proposed using seven (Grams et al. 2017) or six regimes (Falkena et al. 2020). Here different regime numbers ($k = 4, 6, 7$) are computed but we restrict ourselves to showing results for $k = 6$. The results presented are qualitatively similar for each classification, and notable differences will be highlighted throughout the paper.

The clustering algorithm assigns each day to one of the six regimes, even if the daily atmospheric circulation is quite dissimilar to the corresponding (i.e., the nearest) regime. To account for this, a regime attribution is done as a second step. For each regime, a time series is created by projecting the daily Z500 anomaly field onto the regime centroid, following Michel and Rivière (2011). This time series is then normalised, and for each day, the highest regime index is selected. Where this index exceeds one standard deviation, the day is attributed to the corresponding regime. Otherwise, the day is attributed to a 'neutral regime', indicating that the atmospheric circulation of that day is too dissimilar to any of the regimes in question.

The six regimes selected here include the classical four weather regimes, namely: the Atlantic Ridge (AtR), positive and negative North Atlantic Oscillation (NAO+/−), and Scandinavian Blocking (ScBl). They additionally include the Atlantic Trough (AtTr) and Scandinavian Trough (ScTr). Figure 1 presents the Z500 absolute and anomaly composites of all six regimes. The AtTr regime has a cyclonic anomaly over the British Isles and two anti-cyclonic anomalies to the west and east, compared to the AtR regime, which has an anti-cyclonic anomaly over the North Atlantic, to the west of the British Isles. The additional regimes split the classical NAO+ into two different configurations with a clearly zonal pattern for the ScTr, while the NAO+ defined in this categorisation shows a cyclonic anomaly over southern Greenland and an anti-cyclonic anomaly over northern Europe. It is important to note this difference with the classical representation of the NAO+ as it leads to different surface impacts, compared to what is generally understood (see Section 3.4). The ScTr and AtTr regimes in this paper correspond to the Scandinavian Blocking negative and Atlantic Ridge negative regimes, respectively, in fig. 6 of Falkena et al. (2020).

Most regimes have a frequency around 10% to 12% with the ScBl, ScTr and AtR regimes being slightly more frequent at ~14%. The neutral days are even more frequent, around 18%. The frequency of regimes across the cold season varies from month to month, with most regimes being more frequent during the DJF period, while the neutral days are most frequent in October and April. The higher frequency of neutral regimes during the transition seasons is in line with previous studies (Grams et al. 2017; Osman et al. 2023). The average persistence of regimes is fairly similar at around 3 days, with the NAO− regime being most persistent (4 days) and the NAO+ and neutral regimes being least persistent (2 days).

3 | Results

3.1 | Characteristics of Energy Days

In this section, the characteristics of energy days, including their inter-relationships and how these vary from country to country, are discussed. This is done by a thorough analysis of all 28 countries included in the dataset (see Supporting Information), and all general statements made here are based on the full analysis. However, for illustrative purposes, for the most part, only a subset of countries is shown in the body of the paper to limit the number of figures. France and Germany are shown in most figures as they offer a study in contrasts; although they are neighbours with similar demography, France has very little installed wind capacity, whereas Germany has a high wind capacity. The

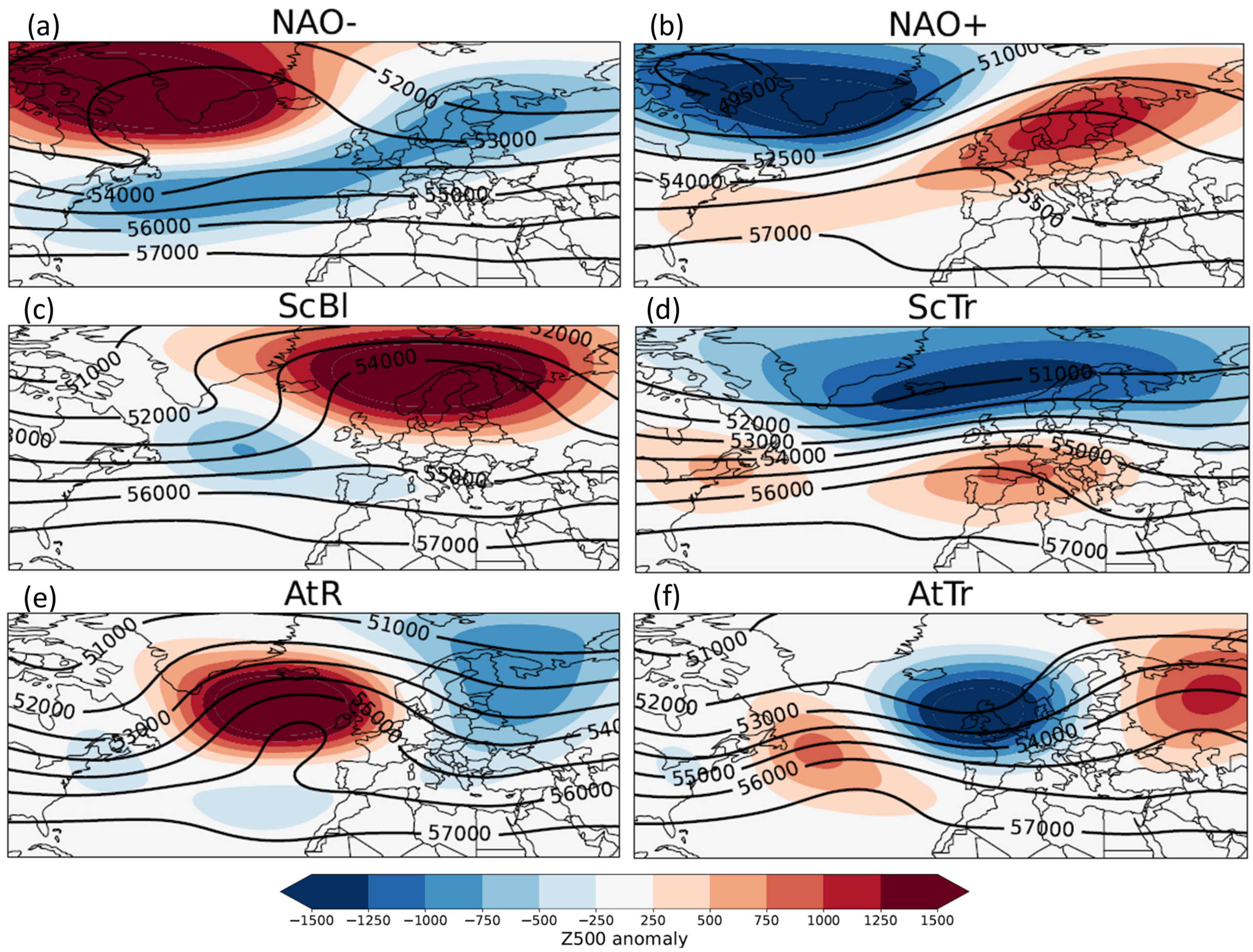

FIGURE 1 | Composites of all six regimes: NAO− (a), NAO+ (b), ScBl (c), ScTr (d), AtR (e), AtTr (f). Colours show the Z500 anomaly and the contouring shows the Z500 absolute values.

importance of this difference will be apparent in the results. If further differences are observed in other countries, they are described and, in some cases, shown.

We first compute time series of annual frequencies (see Figure 2, e.g., of France and Germany). Although long-term trends are not the focus of this study, we nevertheless make a few comments on the trends, given their presence in the time series. While there is no significant trend in the frequency of both solar and wind drought days across all countries, demand days see a statistically significant decrease in frequency for all countries at the 95% confidence level using a bootstrap resampling method. This decrease in frequency of demand days is anti-correlated with the increase in winter temperatures (October to April included) for each country (e.g., −0.80 and −0.86 Pearson correlation for France and Germany, respectively; see Figures S5–S7 for other countries), suggesting it is related to climate change. This relationship between energy demand and temperature is consistent with that found in previous studies (Bloomfield et al. 2020a).

It is important to highlight that the trends shown here arise from meteorological factors alone, as the energy dataset used is idealised and does not account for societal changes or changes in energy infrastructure. As such, the trends show the sensitivity of the current energy system to changes in climate and are counter-factual in nature. The actual trends would be affected by socio-economic factors, not just by changes in the energy system. As an example, the population of France rose from 55 million in 1982 to 67 million in 2020 (INSEE 2021).

Shortfall days also see a decrease in frequency for all countries; however, the magnitude of the decrease compared to that of demand days varies across countries. In the case of France and Germany, they have a similar trend of decreasing frequency of demand days. However, the decrease in shortfall days is much higher in France (−0.33 days/year) than in Germany (−0.06 day/year, Figure 2), and is only statistically significant (based on a two-sided Student's *t*-test) for France, not Germany. Overall, while the decrease in demand days is statistically significant for all countries, the decrease in shortfall days is only statistically significant for one-half of them. We can understand this result by looking at the difference between France and Germany. In Figure 2b,e, the correlation between shortfall days and winter national 2mT is much higher for France than for Germany. However, in Figure 2c,f, the correlation between shortfall and wind days is much higher for Germany than for France. This suggests that the difference in the shortfall trends between the two countries is related to the difference in sensitivity of shortfall to demand and wind generation. This reasoning can be applied to all 28 countries

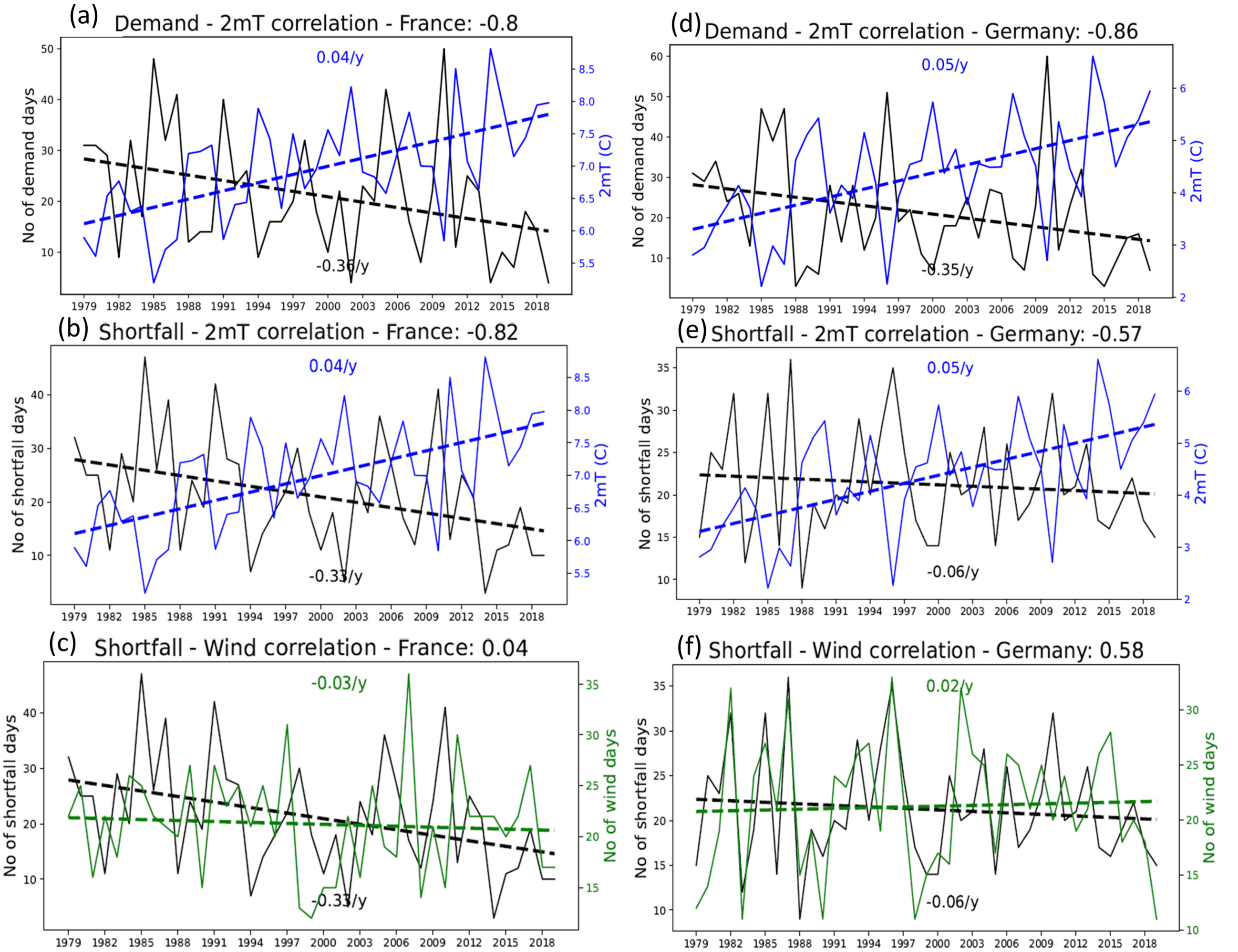

FIGURE 2 | Yearly frequency of demand and shortfall days during the period 1979–2019 for France (a, b and c) and Germany (d, e and f). Panels a, b, d and e include winter mean 2mT while panels c and f show the yearly wind days frequency. The dashed line shows the associated linear trend. The value shows the slope of the linear trend in days per year, while the correlation between both variables in each panel is included in the panel label.

and highlights distinct groups of countries. Those countries with higher wind capacity (e.g., Germany, Denmark; see Figure S1) and/or located in regions with warmer climates (e.g., around the Mediterranean basin) see similar results as found for Germany, with only a small decrease in shortfall days frequency. On the other hand, those countries with lower installed wind capacity (e.g., France, Switzerland; see Figure S4) and/or located in colder climatic regions (e.g., Norway, Finland; see Figures S2 and S3) experience a stronger decrease in shortfall days frequency. In the first group of countries, shortfall is less sensitive to temperature and therefore to demand, and more sensitive to wind conditions, while the opposite is the case in the second group.

This difference between the two groups of countries is also evident when looking at the monthly distribution of energy days (shown in Figure 3 for the case of France and Germany). The energy demand days are generally more frequent during the coldest months of the winter (December, January, February; DJF) and less during the transition months (October, November, March, April), as expected. Similarly, most solar drought days occur in DJF as daylight is reduced. For wind drought days, the monthly distinction is less clear, but generally, DJF is associated with windier conditions (Laurila et al. 2021; Molina et al. 2021) and less frequent low wind conditions across Europe (Gutiérrez et al. 2024). Therefore, most wind drought days occur during the transition months.

While these characteristics are common across all countries, for shortfall days the two groups of countries exhibit differences. In particular, countries with high installed wind capacity such as Germany (Figure 3h) have a broader distribution of shortfall days across the months compared to countries with lower installed wind capacity such as France (Figure 3d), where shortfall is more closely linked to temperature. This figure highlights the strength of the seasonality of demand in relation to the seasonality of wind. An important caveat is that the dataset is idealised to extract the impact of weather on energy without confounding factors from changes in the energy system, which might not take into account the level of weather dependence of demand.

To further understand the differences between European countries, the percentage of shortfall days coinciding with demand, wind drought and solar drought days is displayed in Figure 4 (see Figures S8 and S9 for other countries). This illustrates that for

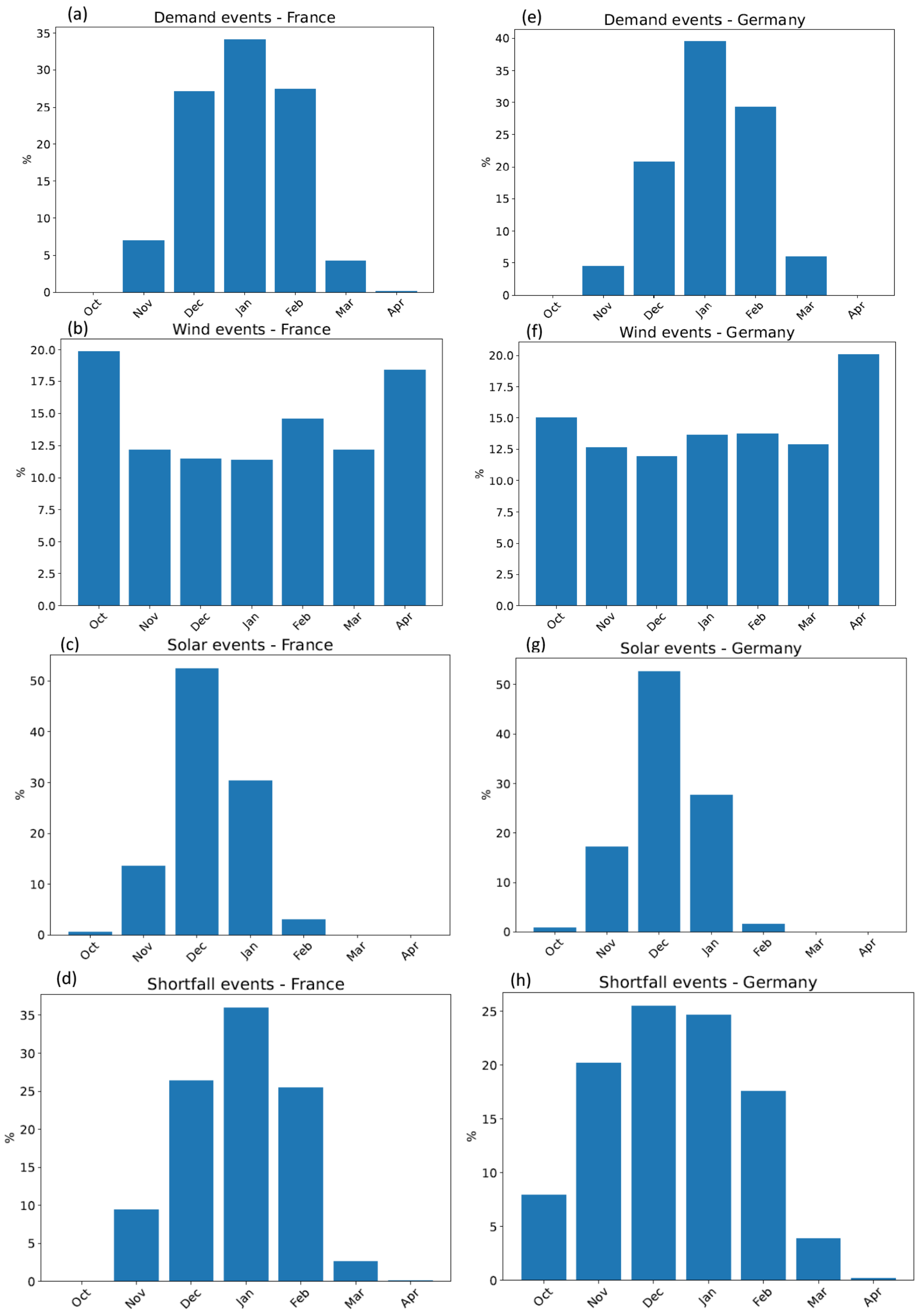

FIGURE 3 | Frequency of energy days during each winter month for France (a–d) and Germany (e–h).

countries with lower installed wind capacity (e.g., France) and countries in cold climates (e.g., Finland), the shortfall days coincide largely with demand days (Figure 4a,b). On the other hand, countries with high installed wind capacity (e.g., Germany) and countries in warmer climates (e.g., Italy) have shortfall days that overlap mostly with wind drought days (Figure 4c,d).

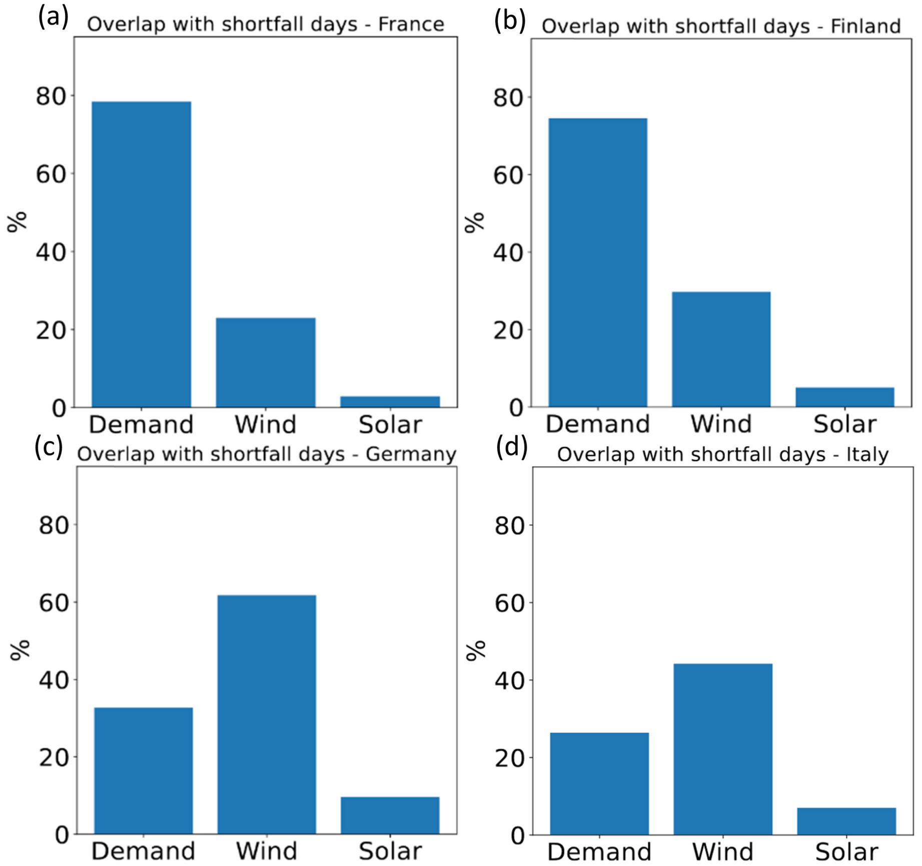

FIGURE 4 | Percentage of shortfall days coinciding with demand, wind and solar drought days for France, Finland, Germany and Italy.

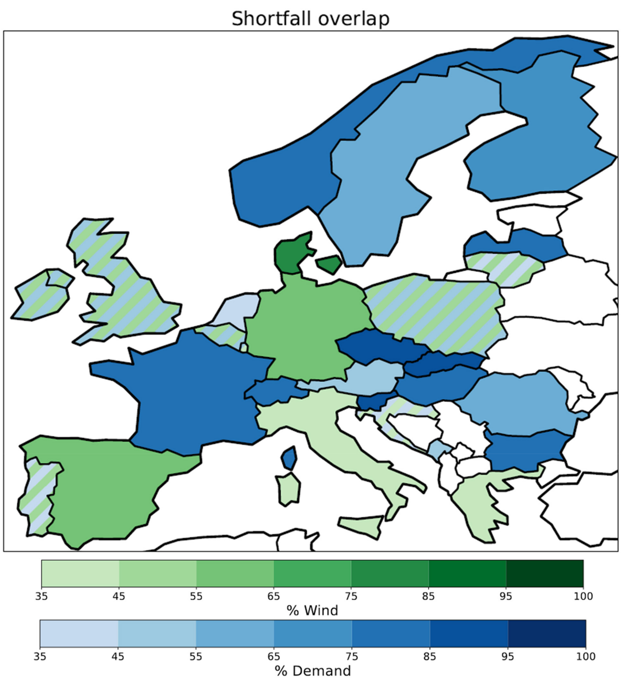

FIGURE 5 | Percentage of wind days (for countries whose shortfall days overlap most with wind days) or demand days (for countries whose shortfall days overlap most with demand days) coinciding with shortfall days. Stripes show countries for which the percentage of shortfall days overlapping with wind or demand days is within 10%.

Figure 5 shows which countries have shortfall days that mainly coincide with demand or wind drought days, together with the respective percentages. The patterns seen across Europe help explain the behaviour discussed earlier in the context of Figures 1 and 2.

This sensitivity to demand or wind depends on both the energy network of the country and the climatic region. For countries further north and/or with limited installed wind capacity, the shortfall is mainly dependent on demand. For countries further south and/or with high installed wind capacity, the shortfall is mainly dependent on wind generation.

Figure 6 further represents the association between shortfall days and either demand or wind days in a scatter plot including each country. The countries are colour-coded by their climatological winter mean temperature in the top panel and by the ratio of theoretical daily maximum wind generation (wind installed capacity multiplied by 24 h) to mean demand in the bottom panel (representing the installed wind capacity). Countries for which shortfall days overlap mostly with demand days (top left corner of each panel) have generally either colder climates (e.g., Norway, Latvia, Finland) or low installed wind capacity (e.g., France, Bulgaria). Countries for which shortfall days overlap mostly with low wind days (bottom right corner of each panel) have generally warmer climates (e.g., Spain, Italy, Greece) or higher installed wind capacity (e.g., Germany, Denmark, United Kingdom). There is, of course, a continuous

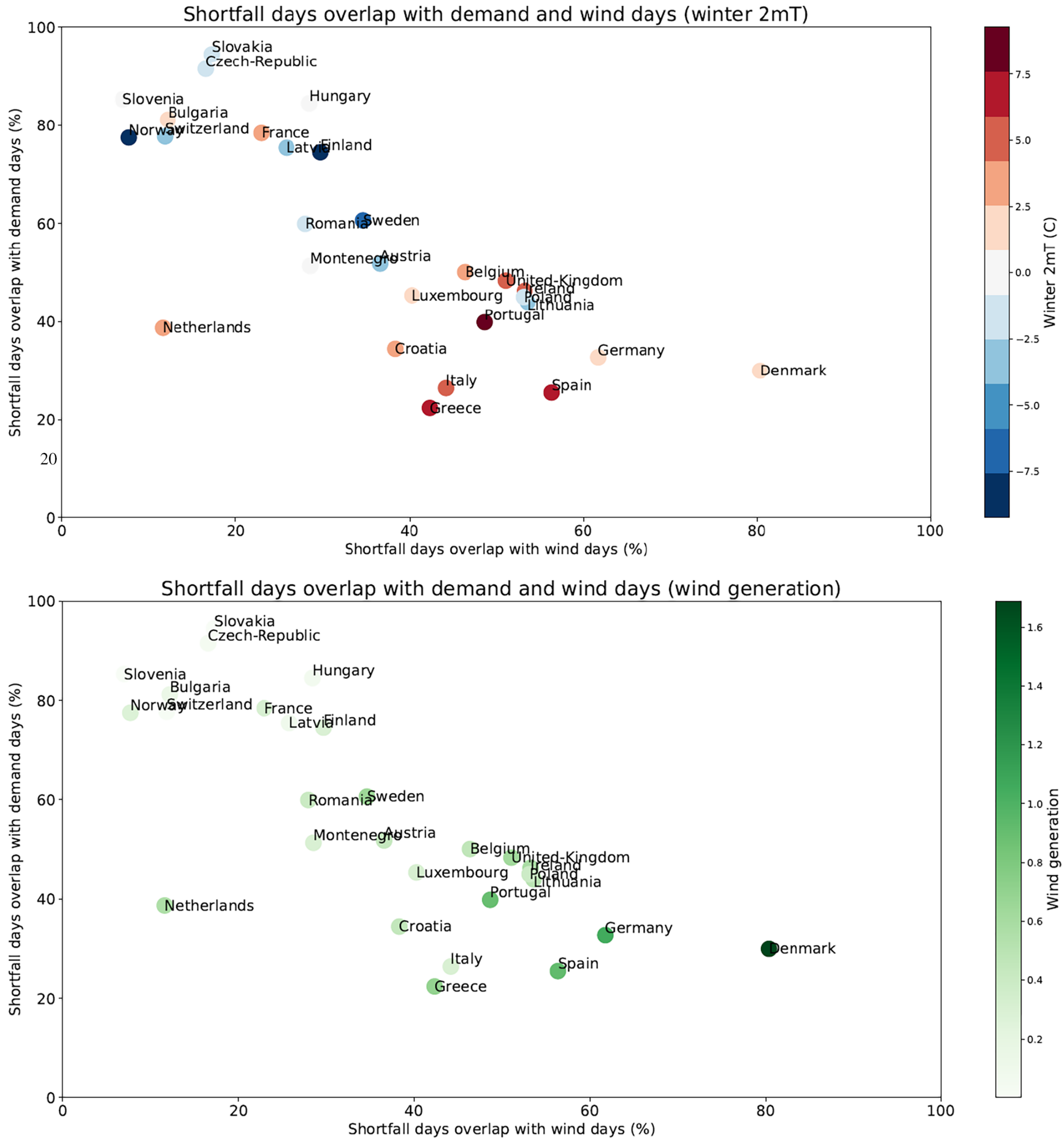

FIGURE 6 | Scatter plot showing the percentage of overlap between shortfall days and demand days on the y-axis and the percentage of overlap between shortfall days and wind days on the *x*-axis, for the 28 countries (each marker is named after the country). The top figure also includes the winter mean temperature while the bottom figure includes the wind generation, in colours.

spectrum in between; for example, Poland and Lithuania are countries that can experience cold conditions but also have a relatively high installed wind capacity; therefore, both demand and wind have a similar importance for shortfall. This analysis highlights how the sensitivity of high shortfall to either high demand or low wind across Europe can be explained by a combination of climatic differences and energy system differences. The finding is consistent with Bloomfield et al. (2018) and also Bloomfield et al. (2020a), who showed how the increase in installed wind capacity changes the sensitivity of shortfall to demand and wind CF.

3.2 | Characteristics of Energy Events

We next investigate whether the duration of energy events (i.e., consecutive energy days) is associated with their intensity. For this comparison, Figure 7 shows the average and maximum shortfall values during brief and long shortfall events in France and Germany (see Figures S10–S12 for other countries). As the two countries have different energy systems and therefore also their average shortfall length varies, shortfall is normalised by removing the climatological shortfall and dividing by the standard deviation, allowing for a better comparison.

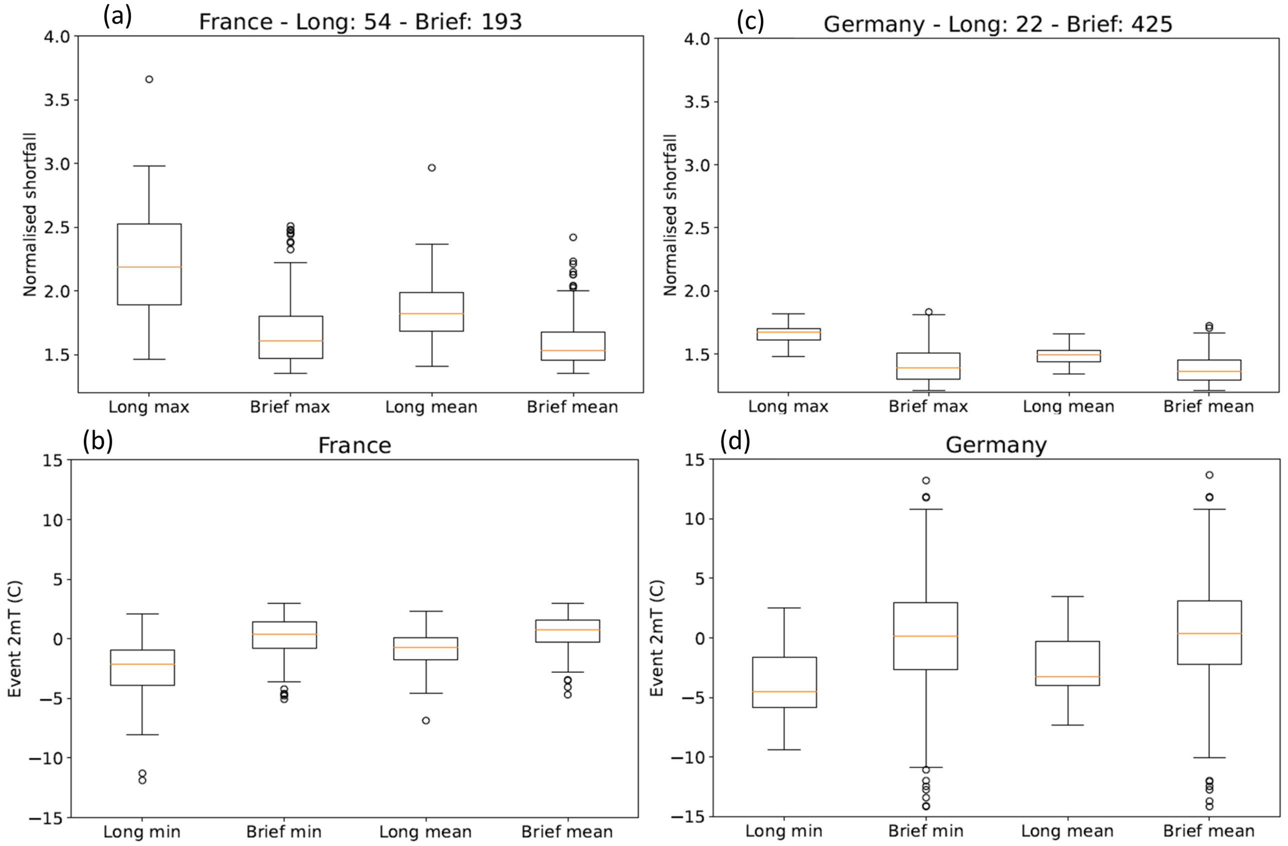

FIGURE 7 | Boxplots comparing values during long and brief shortfall events, for the case of France and Germany. (a and c) Show the maximum daily shortfall value reached during an event and the mean daily shortfall values across an event. (b and d) Show the minimum daily 2mT reached and the mean daily 2mT across an event. The box represents the 25th and 75th percentile range, while the orange line shows the median value. Whiskers show the 10th to 90th percentile range while the circles show outliers.

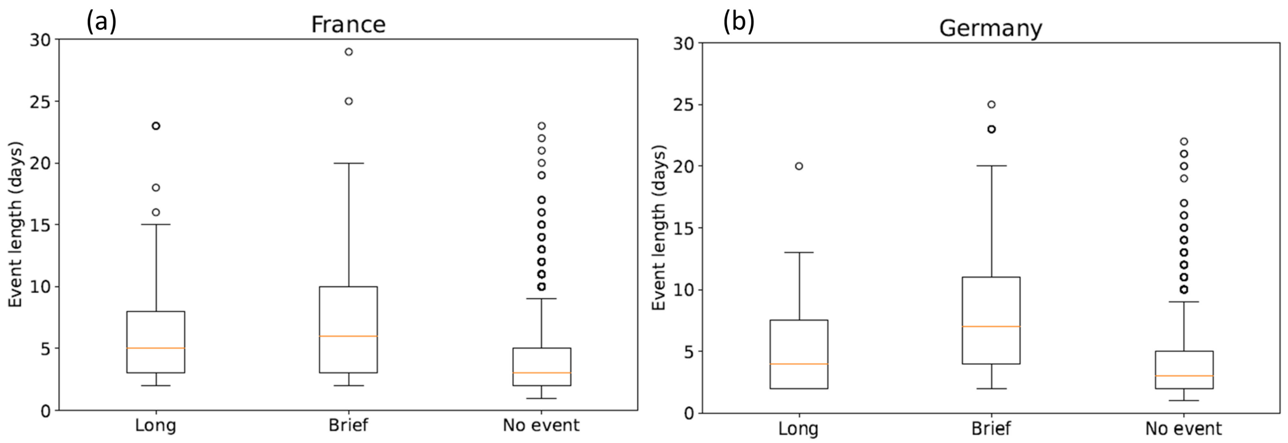

FIGURE 8 | Persistence of weather regime events which occur during long or brief shortfall events and weather regimes which do not coincide with shortfall events, in France (a) and Germany (b).

Both average and maximum shortfall values are higher during long shortfall events compared to brief shortfall events. Similarly, demand values are higher and wind CF is lower during long shortfall events (not shown). This is consistent with the fact that long events are also associated with lower temperatures than brief events (Figure 7b,d). The conclusion is the same when defining shortfall days as days where shortfall is above the 95th percentile, although the statistics then get even noisier. While only France and Germany are shown here, this observation is applicable to other countries as well (see Figures S13–S15). This means that extreme energy conditions are often persistent for several day. van der Wiel, Bloomfield, et al. (2019) showed that energy conditions get progressively extreme before energy events, supporting the notion that extreme energy conditions are preceded by days with high-energy demand and shortfall, and low wind CF.

To determine the potential cause of the differences between long and brief events, Figure 8 compares the persistence of weather regimes during long, brief and no events for France and Germany (see Figures S16–S18 for other countries). For each

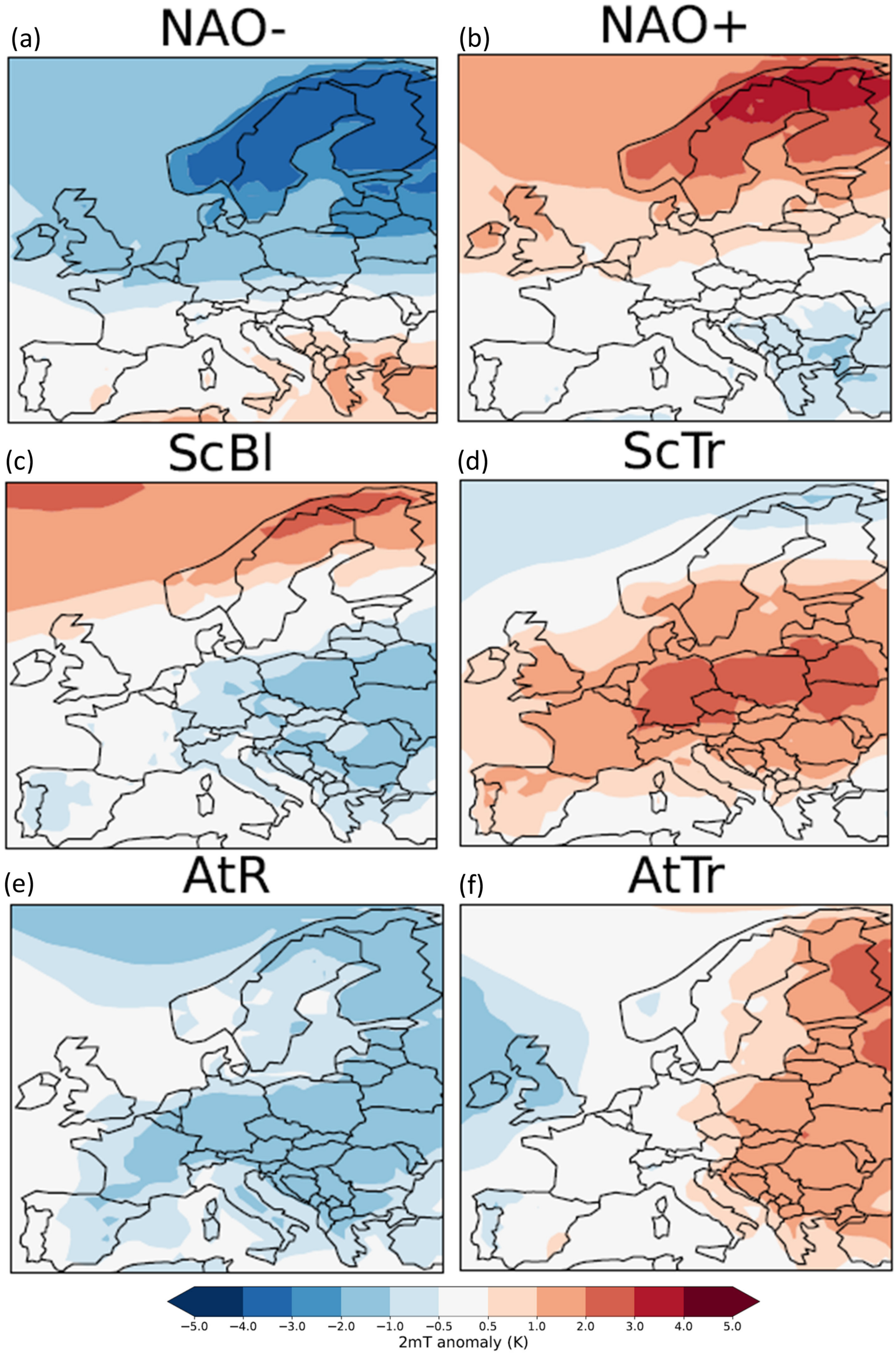

FIGURE 9 | Composites of all six regimes: NAO− (a), NAO+ (b), ScBl (c), ScTr (d), AtR (e), AtTr (f). Colours show the 2mT anomaly.

energy event, all regime events (consecutive days assigned to one regime) that coincide with the energy event are included. This shows that weather regimes are more persistent during shortfall events. However, the persistence of weather regimes does not appear to depend on whether the shortfall events are long or brief (Figure 8). The analysis nevertheless suggests that shortfall events are more likely during more persistent weather regimes.

3.3 | Surface Impacts of Weather Regimes

Before analysing the links between weather regimes and energy events, we describe the imprint of weather regimes on European weather. For this set of weather regimes, which has not yet been investigated for its impact on surface weather or on energy, it is important to discuss the relationship between the weather regimes and surface conditions. This allows us to better understand how the weather regimes can impact energy.

To understand the relative influence of the weather regimes on energy variables, we show the regime composites of 2mT (Figure 9) and W10m (Figure 10). As expected, low temperatures across several countries are associated with the AtR, ScBl, and NAO− regimes (Figure 9). The NAO− regime (Figure 9a) affects most of northern Europe with negative anomalies extending to southern Germany and northern France while temperatures reach close to 4° below climatology over Scandinavia. The ScBl regime (Figure 9c) leads to lower temperatures over eastern Europe from Ukraine to Germany, but the anomalies are less strong. Negative temperature anomalies during the AtR regime (Figure 9e) cover all of Europe with the strongest anomalies concentrated over continental Europe, from France to the Baltic countries. It is important to note that the 2mT anomaly of these weather regimes differs from that of the classical four regimes. For instance, the warmer anomaly centred over Scandinavia during NAO+ regime days extends to most of Europe in the classical four regimes (van der Wiel, Bloomfield, et al. 2019; van der Wiel, Stoop, et al. 2019).

These same regimes are associated with low wind conditions over some regions of Europe (Figure 10). The negative wind anomalies cover fewer countries but generally affect similar or neighboring regions. These regimes (AtR, ScBl and NAO−) lead to lower wind conditions across northern Europe and the western coasts (Figure 10a,c,e) where a lot of the offshore wind farms are located. The NAO+ and AtTr regimes also show negative wind anomalies over northern Europe and Scandinavia (Figure 10b,d), respectively. Similarly to the case with 2mT,

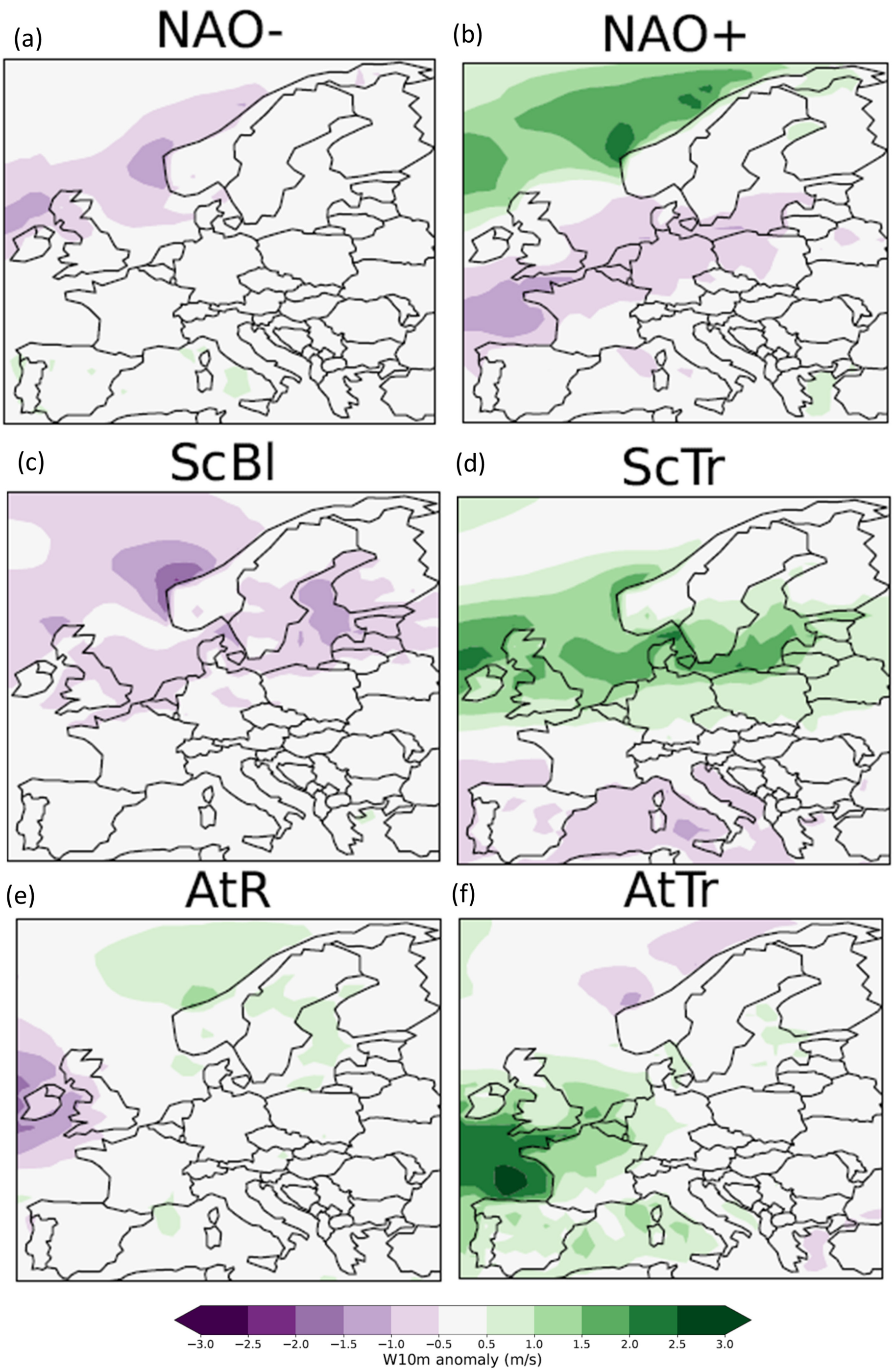

FIGURE 10 | Composites of all six regimes: NAO− (a), NAO+ (b), ScBl (c), ScTr (d), AtR (e), AtTr (f). Colours show the W10m anomaly.

W10m during these regimes differs compared to that in other regime definitions (Michelangeli et al. 1995; Grams et al. 2017). In particular, the classical four regimes associate higher wind conditions during NAO+ days for northern Europe (van der Wiel, Bloomfield, et al. 2019; van der Wiel, Stoop, et al. 2019; Grams et al. 2017). However, in this classification, only northern Scotland and the western coast of Scandinavia are associated with windier conditions, while Germany and Denmark, and in particular the North Sea, experience lower wind conditions.

Solar conditions are less relevant during the winter compared to summer due to shorter periods of daylight (see Figure 4), solar conditions during these weather regimes are not shown. As seen in Section 3.1, for some countries, high shortfall is mostly due to colder conditions, while for other countries, lower wind conditions are also important. Therefore, as the ScBl, NAO−, and AtR regimes lead to both colder and lower wind conditions across large parts of Europe, even though not necessarily in the same regions, these regimes are most likely to lead to higher energy shortfall.

3.4 | Influence of Weather Regimes on Energy Days

In the following section, energy days and weather regimes are brought together by examining the relationship between them to look at patterns across the continent.

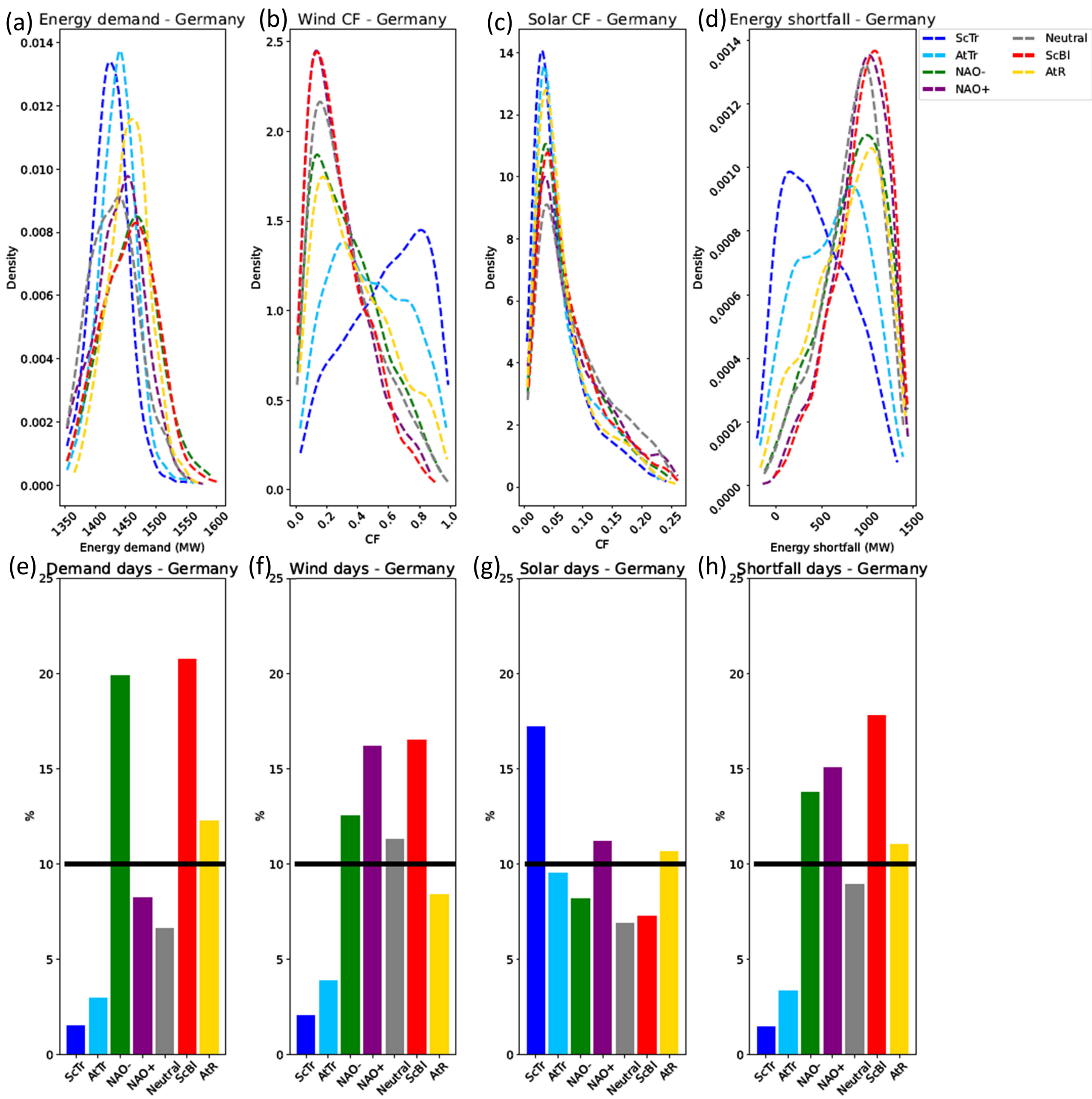

FIGURE 11 | Energy distribution during each weather regime and each energy variable for Germany (a–d). Energy demand and shortfall are shown in megawatts (MW). Conditional probability of energy days during each weather regime (e–h). The black line shows the climatological probability of each energy day (10% by definition).

3.4.1 | Impact of Weather Regimes Across Europe

The energy distribution is shown during the different weather regimes for each energy variable for Germany (Figure 11a–d). Only the distribution of wind CF (Figure 11b) and of energy shortfall during the ScTr regime is visually distinct from that in other regimes. For other countries with less installed wind capacity, even less of a difference between regime distributions is visible. For those countries, the other regimes are almost indistinguishable from each other, making any characterisation of the typical energy situation during each regime quite difficult. However, Figure 11e–h shows the conditional probability of energy days during each regime, highlighting the information regimes provide for energy days. This conditional probability is defined as the number of demand days during ScTr days, for example, divided by the number of ScTr regime days. The black horizontal line shows the climatological probability of energy days (by definition 10%) and highlights how the conditional probability differs from the climatological probability. For example, the ScBl and NAO− regimes are associated with a higher probability of demand days (Figure 11e). Thus, while looking at the full distribution is not helpful in identifying the influence of the different weather regimes, the focus on extreme values, represented here by the energy days, reveals their impact.

Otero et al. (2022) observe similar results; however, they look at the frequency of weather regimes during shortfall (Energy Compound Events in the article) which is subject to the climatology frequency of weather regimes and neutral days. Using conditional probability here better highlights how some weather regimes favour the occurrence of a shortfall.

To identify differences between countries, the weather regime with the highest conditional probability for each energy day is shown for the individual countries on a map (Figure 12).

When considering demand and shortfall days in particular (Figure 12a,d), Europe appears split. Scandinavia, Denmark, the British Isles, and the Baltic countries all have the NAO− regime as the one regime with the highest conditional probability of high demand days to occur, while for most of central Europe it is the ScBl regime (Figure 12a), and for the Mediterranean countries and Portugal it is the AtR regime. For shortfall days (Figure 12d), it is a very similar situation

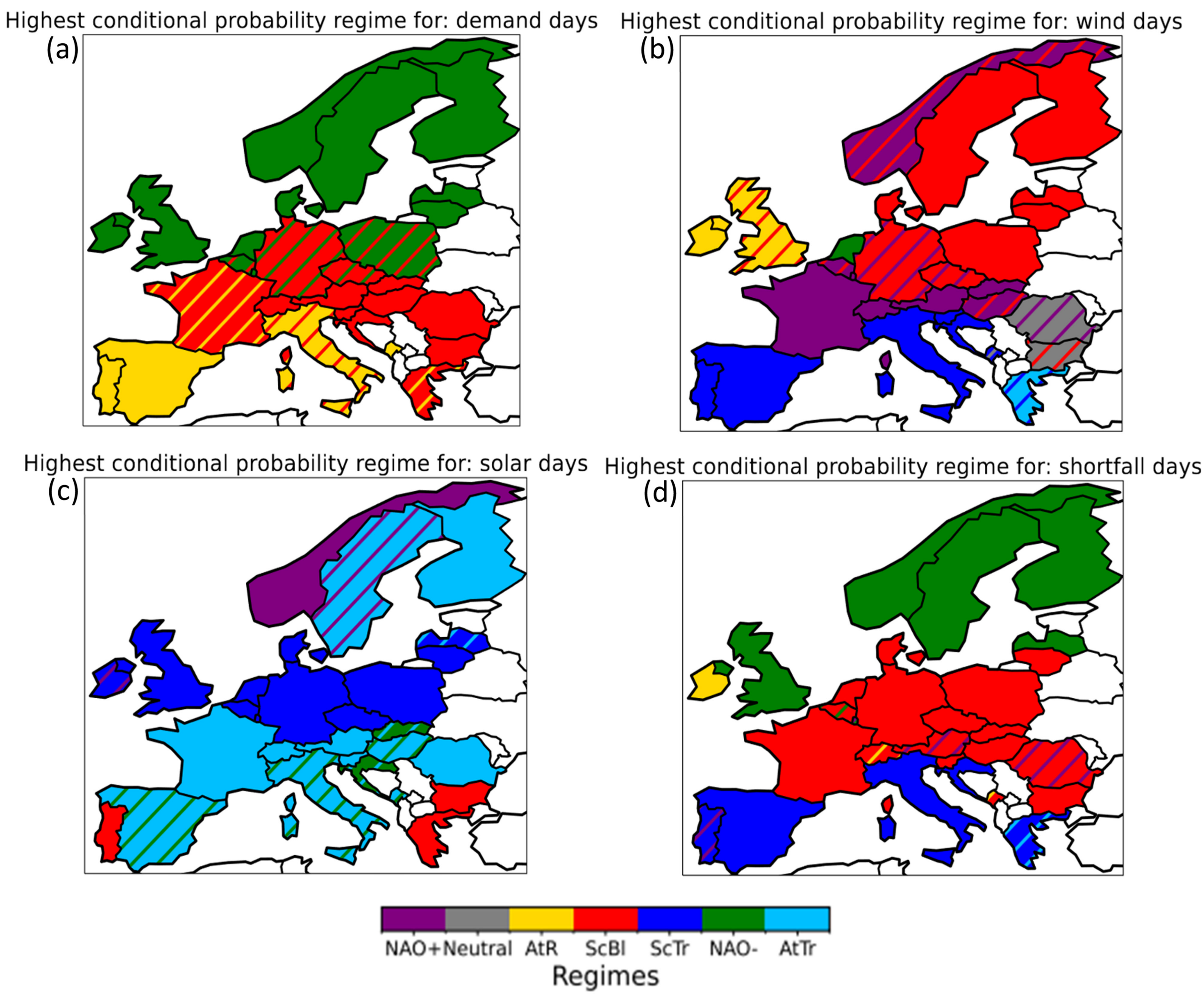

FIGURE 12 | Regimes with the highest conditional probability of demand (a), wind (b), solar drought (c) and shortfall days (d) to occur. The stripes also show the regime with second-highest conditional probability if it is within 2% of the highest.

with the notable exception of southern countries being more affected by the ScTr regime. Other regime classifications give similar results, with blocking type regimes being dominant for most countries for demand and shortfall days (not shown). Similar results are found in previous work using different classifications (Bloomfield et al. 2020a; van der Wiel, Stoop, et al. 2019; Otero et al. 2022). A notable difference is the European Blocking regime being more represented than the ScBl regime for high shortfall days for the classification with seven regimes. Compared to the ScBl regime, the European Blocking regime's anti-cyclonic anomaly is centred more over the British Isles and not the Scandinavian region.

Figure 12 suggests that when, for instance, the ScBl regime is active, it is possible for a large number of European countries to be affected by high demand and shortfall days simultaneously. This raises the question of whether multiple countries can suffer from simultaneous high shortfall days, and if so, what would be the impact on neighbouring countries and what are the atmospheric conditions associated with such situations. This question is addressed in the following section.

3.4.2 | Connected Countries

In the context of this study, the assumption is that countries within each RSC (see Section 2) are well interconnected in their energy power systems. Currently, the assumption of good interconnection might not be the most realistic as RSCs have limited power compared to national TSOs, and the export–import capacity is in some cases limited. For France and Spain, it is currently at only 2.8 GW. However, the increase in

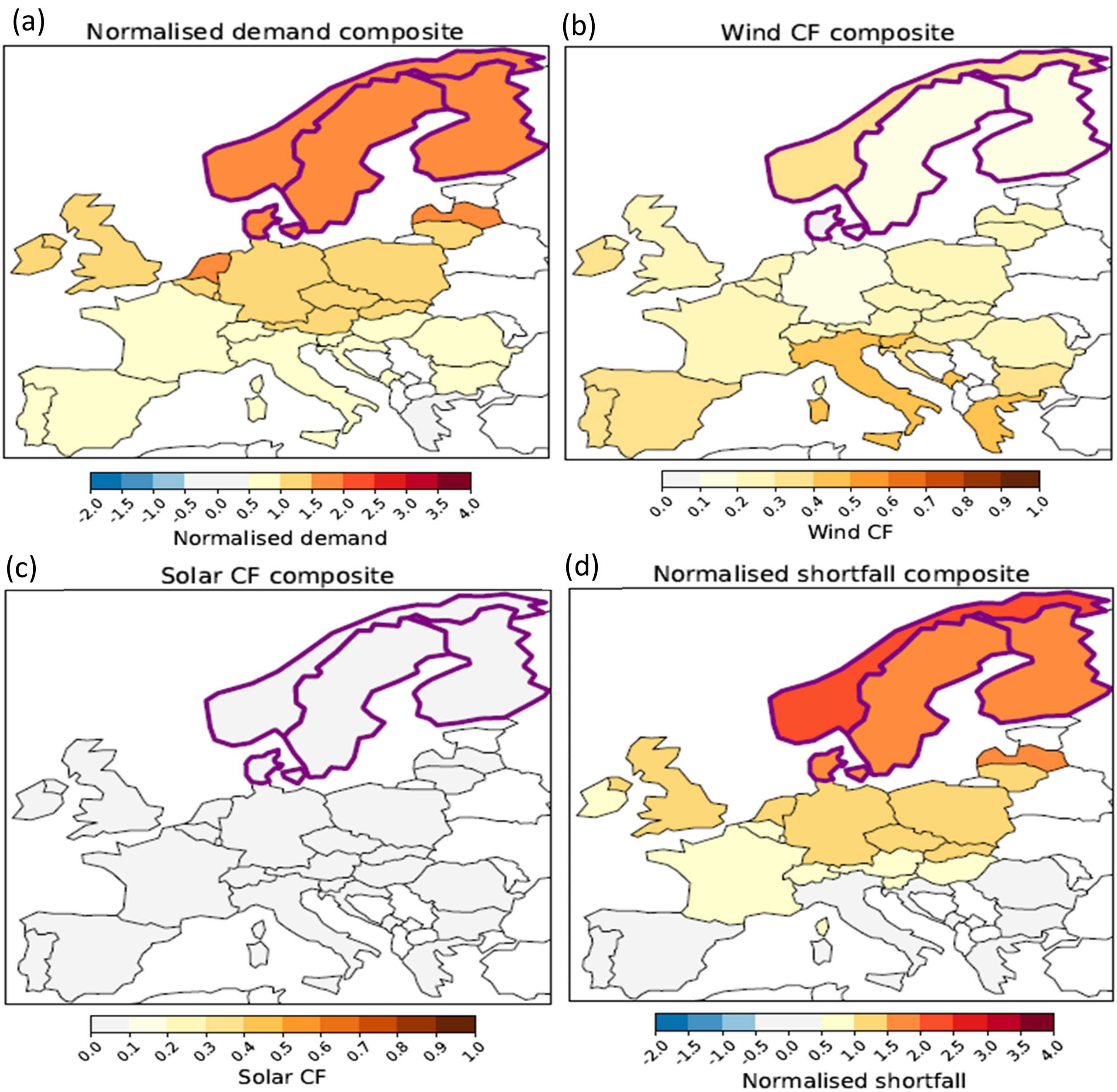

FIGURE 13 | Energy composites during common shortfall days of Nordic RSC. Demand (a); wind CF (b); solar CF (c); shortfall (d). Purple contours show the countries that are part of the Nordic RSC.

interconnectivity between countries and the increase in power to RSCs is an objective of the European Union (European Commission 2010; Electricity Interconnection Targets n.d.; European Environment Agency 2019). Discussing the outcome of common shortfall days under this assumption is thus relevant, given this evolving context. Therefore, based on this assumption, if one country experiences a shortfall, it can draw electric power from countries within the same

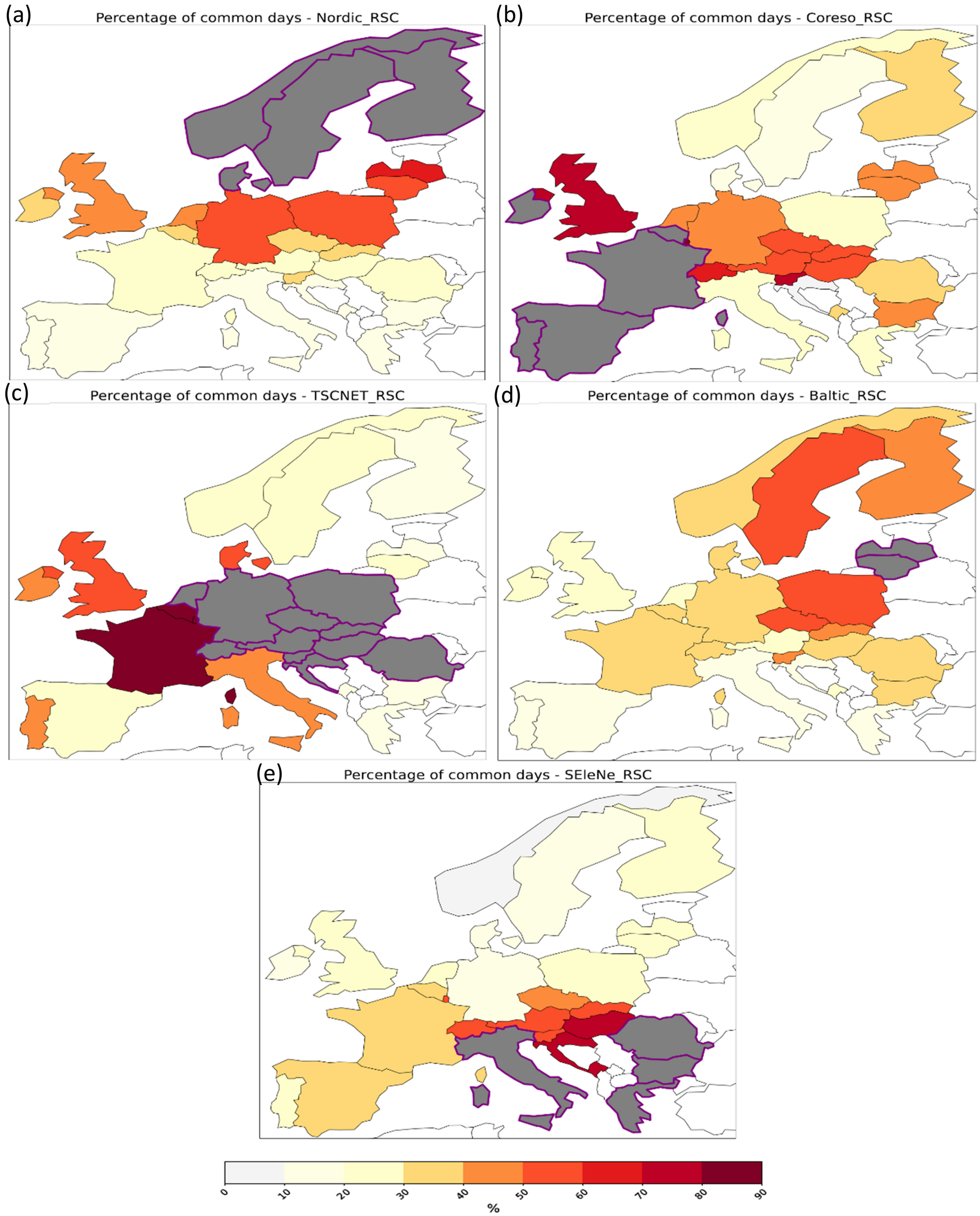

FIGURE 14 | Percentage of shortfall days coinciding with common shortfall days of the Nordic, CORESO, TSCNET, Baltic and SEleNe RSC countries. Purple contours show the countries that are part of the same RSC. These countries are greyed out, as the percentages are 100% for these countries by construction.

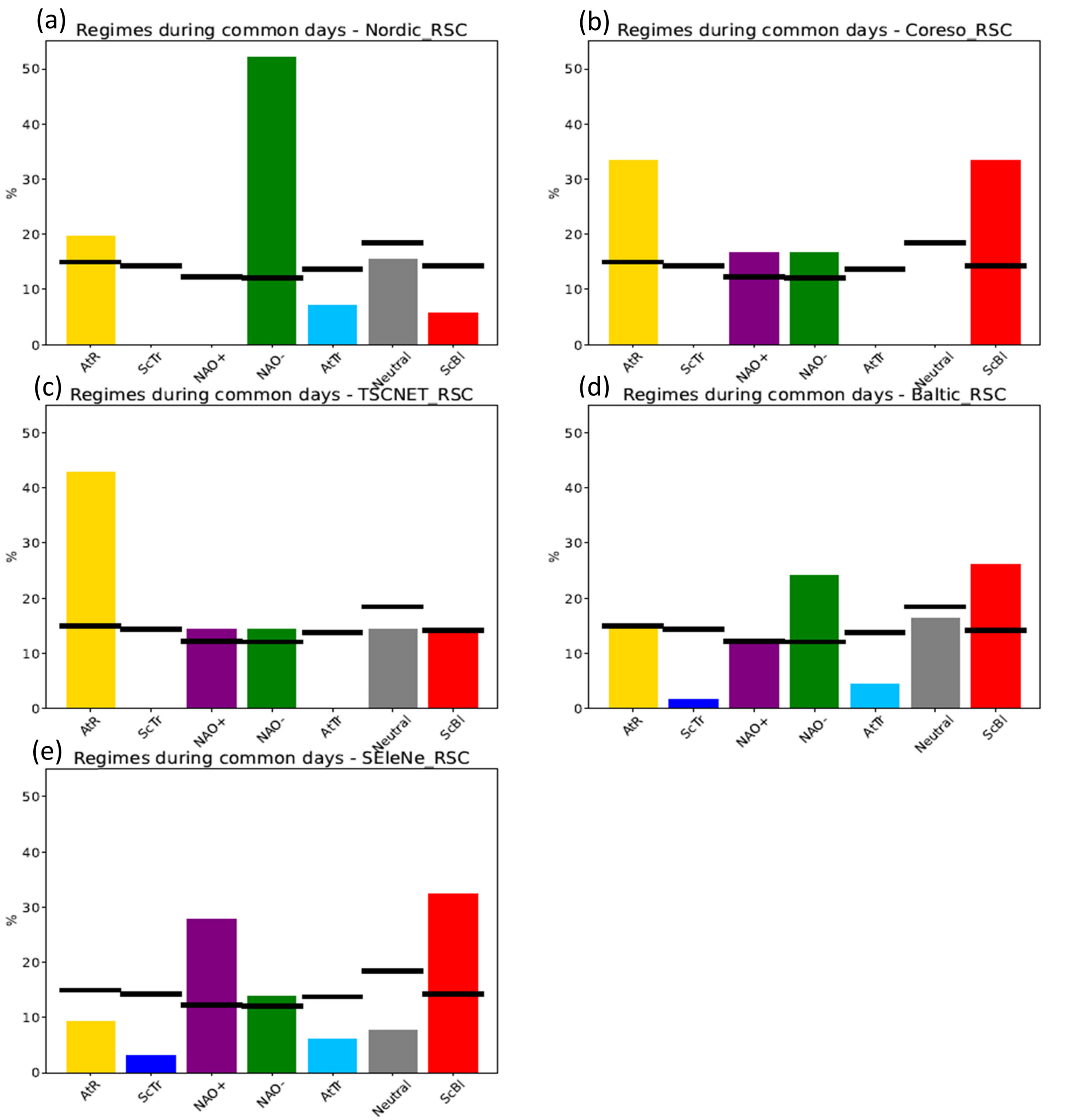

FIGURE 15 | Regime frequency during common shortfall days for the Nordic (a), CORESO (b), TSCNET (c), Baltic (d) and SEleNe (e) RSCs. Black lines show the climatological frequency of each regime.

RSC. However, if all countries or several within the RSC are experiencing a shortfall, this strategy might become difficult. Here, the hypothesis introduced in the previous section that common shortfall days, that is, shortfall days that occur at the same time in all countries of the same RSC, is discussed.

Figure 13 shows the Nordic RSC, including the Scandinavian countries and Denmark as an example. Here, all common shortfall days are averaged, and the normalised demand, shortfall, and the wind and solar CF are shown. Demand and shortfall (Figure 13a,d) are normalised for each country for better comparison between countries, as otherwise, the discrepancy between the demography of each country will obscure any signal. As expected, both shortfall and demand are on average high across all Nordic RSC countries during common shortfall days. Additionally, neighbouring countries also experience anomalously high demand and shortfall. In contrast, countries farther away, and in particular, countries south of the Alps and Pyrenees experience anomalously low shortfall and demand.

These observations are applicable to other RSCs (Figure 14). In the case of RSCs (Nordic, SEleNe) where all countries are north or south of large mountain ranges, the dominant regimes leading to shortfall are NAO− and ScTr, which have a clear North–South difference in surface impact. This could explain the opposite impact on shortfall between countries in Northern and Southern Europe. This also highlights how interconnections with neighbouring countries would not be as helpful in situations of shortfall.

Simultaneous shortfall days are also mostly associated with blocking type regimes. Figure 15 highlights that the most frequent regimes are ScBl, AtR and NAO− which are characterised by blocking-type atmospheric conditions. Only the SEleNe RSC, which includes Greece and Bulgaria, sees the NAO+ regimes being very frequent during common shortfall days.

The prevalence of blocking-type regimes is further emphasized by looking at Z500 composites during the common shortfall days (Figure 16), showing a ridge formed over western Europe for all RSCs. The exact position and extent of this ridge determine the area that is likely to experience colder conditions or lower winds and therefore shortfall. While Figure 15 highlights that these common shortfall days are mainly occurring during the AtR, NAO− or ScBl regimes, the composites in Figure 16 are not so similar to the regime composites in Figure 1. This might highlight that more targeted circulation patterns would show higher correlations with such events (Bloomfield et al. 2020a).

In Section 3.4.1 individual weather regimes (e.g., ScBl, NAO−) have been observed to favour the occurrence of shortfall across large parts of Europe, and therefore multiple countries. The results of this last section confirmed the hypothesis that shortfall days could occur in neighbouring countries concurrently, and underlined how the aforementioned weather regimes are associated with these common shortfall days. The results are consistent with Otero et al. (2022).

3.4.3 | Impact of the Coldest Winter Driven by Persistent Weather Regimes: The Example of Winter 1962–1963

As blocking type weather regimes (AtR, NAO− and ScBl) favour the occurrence of shortfall, potentially over multiple countries, we now study the extreme winter 1962–1963. This winter was characterised by a very persistent NAO−, and is known as the coldest European winter of the 20th century (Hirschi and Sinha 2007). While extremely cold winters are becoming less likely due to a warming climate, similarly cold winters are still possible if such extreme atmospheric circulation conditions as in the winter 1962–1963 were to reoccur (Sippel et al. 2024). Considering this, investigating the winter of 1962–1963 could show what a possible worst-case scenario for the energy sector would look like, not only over a restricted region such as the RSCs seen in the previous section but across all of Europe. This analysis investigates the potential impact such a winter would have on the current (c. 2017) energy infrastructure.

As a first step, the winter of 1962–1963 is characterised by using composites of Z500, 2mT and W10m (Figure 17).

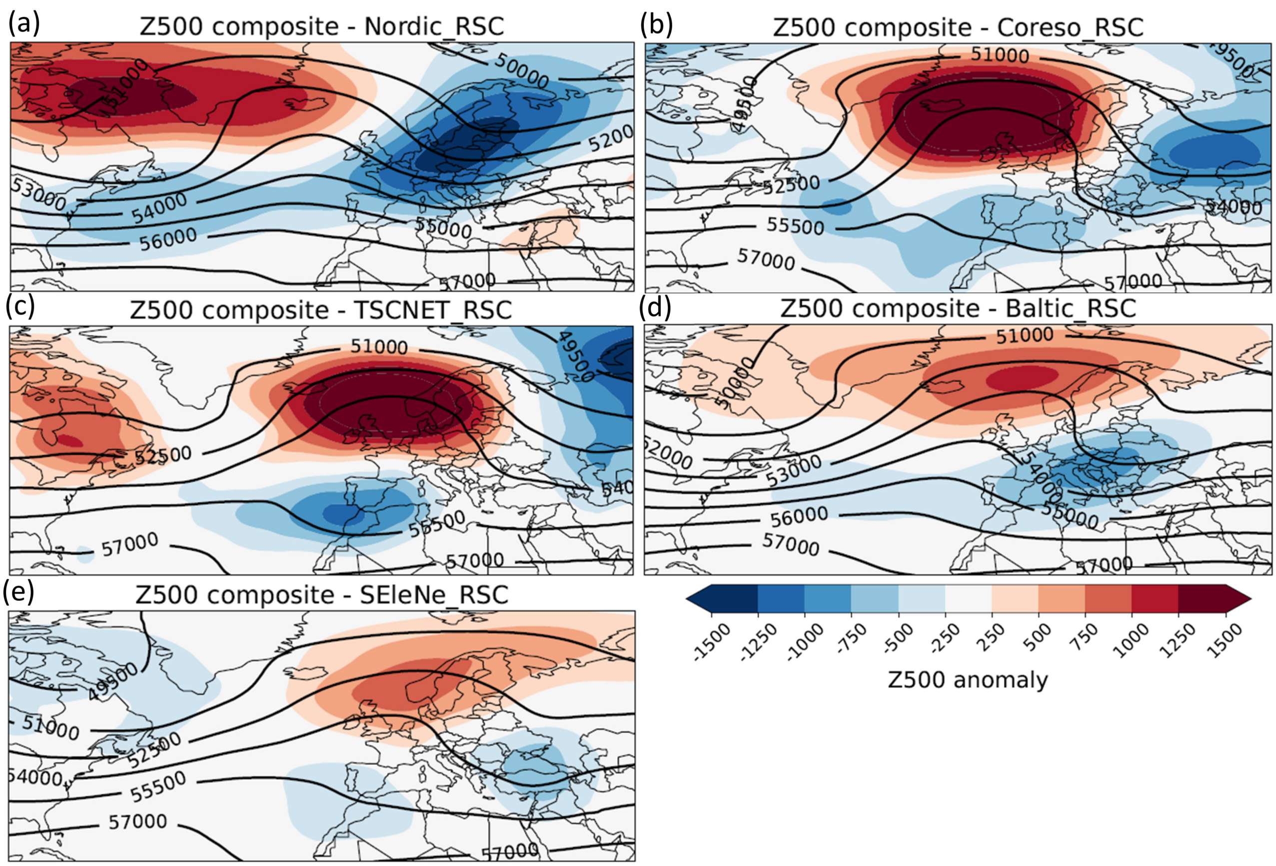

FIGURE 16 | Z500 anomaly in colouring and absolute values in contouring for common shortfall days for the Nordic (a), CORESO (b), TSCNET (c), Baltic (d) and SEleNe (e) RSCs. See grey shadings in Figure 14 for each RSC's countries.

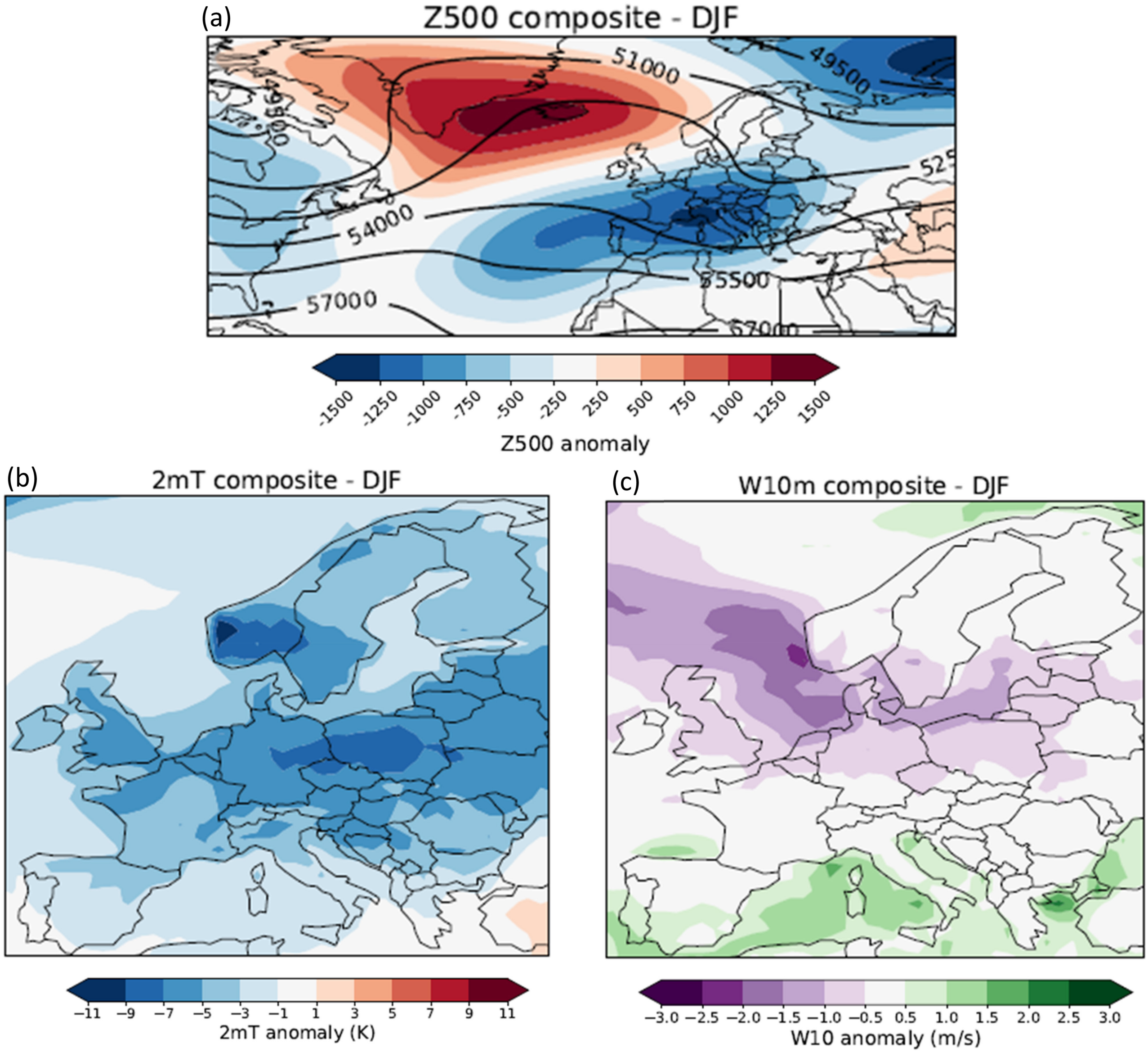

FIGURE 17 | Composites averaged over December, January and February from 1962 to 1963. Z500 absolute values in contours and anomaly in colours (a); 2mT anomaly in colours (b); W10m anomaly in colours (c).

The 2mT composite shows the expected strong negative temperature anomaly across all of Europe (Figure 17b). The atmospheric circulation is characterised by a ridge over western Europe (Figure 17a), similar to that shown in Figure 16. Associated with the ridge, a negative wind anomaly covers the North Sea and parts of northern Europe (Figure 17c). The weather regime frequency during winter (DJF) shows the predominance of the NAO− regime (Figure 18), consistent with prior studies (Hirschi and Sinha 2007; Greatbatch et al. 2015) and the ridge visible in the Z500 composite.

We assess the effect on the energy sector if the winter conditions of 1962–1963 would occur under the current energy infrastructure. It is important to note that the dataset used for this analysis (Bloomfield and Brayshaw 2021) provides wind and solar CF only for 12 different countries.

The energy demand and shortfall in Figure 19 are normalised based on the DJF climatology (mean and standard deviation are done over the DJF period) for a better representation of seasonal variability. Across most countries, the demand is above average, in particular during the months of January and February of 1963, which were particularly cold (not shown). The energy shortfall shows a more contrasting picture, with most countries (within this limited sample of countries) experiencing a higher shortfall than the norm, but some countries show shortfall values more than 2.5 standard deviations above the norm. In particular, Germany and Denmark have shortfall values of above 5 and 7 standard deviations above the norm, respectively.

The discrepancy can be partly explained by Germany and Denmark having lower temperatures already in December (not shown), the lower wind conditions are localised more specifically over the North Sea (Figure 17) which is the location of most wind farms for Germany and Denmark. The colder conditions are associated with more demand days (see Figure S19), but this is the case for multiple countries across northern Europe, suggesting that low wind conditions could be more important for

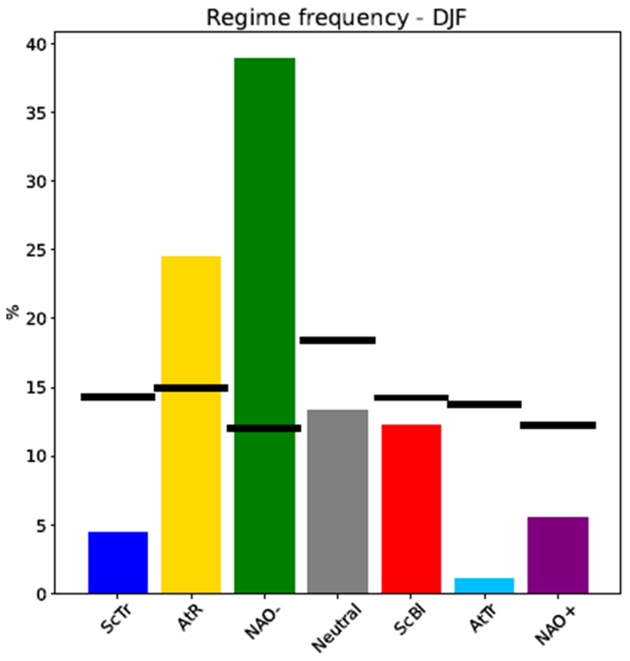

FIGURE 18 | Regime frequency during the 1962–1963 DJF period. Black lines show the climatological frequency of regimes.

Germany and Denmark. Additionally, both countries can, in certain circumstances, have more renewable generation than demand, leading to a negative shortfall (see Figure 11d). This results in a lower value of shortfall standard deviation.

The number of demand and shortfall days is much higher during the 1962–1963 winter compared to other winters (see Figure S19). For most countries, demand days are at least twice as frequent, while for the Netherlands and the United Kingdom, they are up to five times as frequent as for a normal winter. Similarly, shortfall days are at least twice as frequent for most countries and three times as frequent for Norway.

This case study highlights how a winter driven by a persistent blocking type regime, characterised by extreme and persistent cold winter conditions, could affect the current-day energy network in Europe. All countries would experience large demand and shortfall, leading to an increase in extreme energy conditions over a long period of time. These conditions require the preparation and implementation of mitigation plans to limit the impact and reduce the chances of outages, but also to limit the use of more polluting or more expensive energy sources. Additionally, as the large-scale atmospheric circulation was characterised by a very persistent NAO− regime (up to 26 consecutive days in December to January) together with intervals of AtR and ScBl regimes, this underlines again the relationship between weather regimes and shortfall for individual countries and across Europe.

4 | Discussion

Throughout this study, modelled energy data are used with fluctuations being only due to weather conditions. This allows for a clear causal link between meteorological conditions and variations in energy demand and renewable generation without societal and structural or confounding factors blurring the relationship. Furthermore, having a constant infrastructure enables the investigation of more than 40 years of weather on the same relatively current infrastructure. However, the counterfactual nature of the energy dataset used means that direct comparison with real-world energy data is not possible, which is a limitation of the present study. Comparing these results with real-world data would enable us to quantify the relative influence of weather conditions compared with other components (e.g., network constraints, infrastructure, behaviour). Additionally, this study considers daily values; however, large fluctuations do occur during the day, potentially leading to more extreme sub-daily events (e.g., peak demand early evening; Torriti 2017).

There are a number of extensions to this work that might be worth exploring in future studies. While ERA5 is a very useful and practical dataset for this sort of study, using observational datasets or bias-correcting ERA5 could be a useful check. It would also be interesting to examine changes to the energy network following 2030 targets and their impact on the conclusions of this study. This study focused on the winter half of the year; studying the summer period would potentially lead to different regimes being more relevant, solar days being more impactful and different trends in high-demand or shortfall day frequency. Further, the methodology, such as the percentile thresholds, has been chosen to allow comparison between countries with large differences in both demography and infrastructure, and thus may lack the specificity that might be necessary to understand the relationship between energy and weather regimes for individual countries. Lastly, more complex models including storage capacity and interconnection between countries, could provide an even more complex and thorough discussion around difficult situations to balance demand and production.

5 | Conclusions

The transition in Europe towards increased renewable energy generation, in line with the European Green Deal (European Commission 2019), requires a better understanding of the influence of weather conditions on the energy network. Indeed, renewable energy sources such as wind and solar are highly dependent on surface weather, making the balance between energy demand and energy supply more difficult to achieve with more components that can be affected by meteorological conditions (Bloomfield et al. 2016). In particular, periods of increased demand and reduced renewable generation, here called energy shortfall, are crucial.

Several studies have investigated the influence of weather on energy shortfall using weather regimes (Mockert et al. 2023; van der Wiel, Stoop, et al. 2019; Bloomfield et al. 2020a). In this paper, the relationship between shortfall and weather regimes during winter is discussed for 28 European countries. This is done using data of energy demand, wind and solar capacity factors, derived from ERA5 covering the period from 1979 to 2019 with constant energy infrastructure set to 2017 and where each day is treated as a Monday (Bloomfield et al. 2020a). By keeping all network and societal parameters constant, it is possible

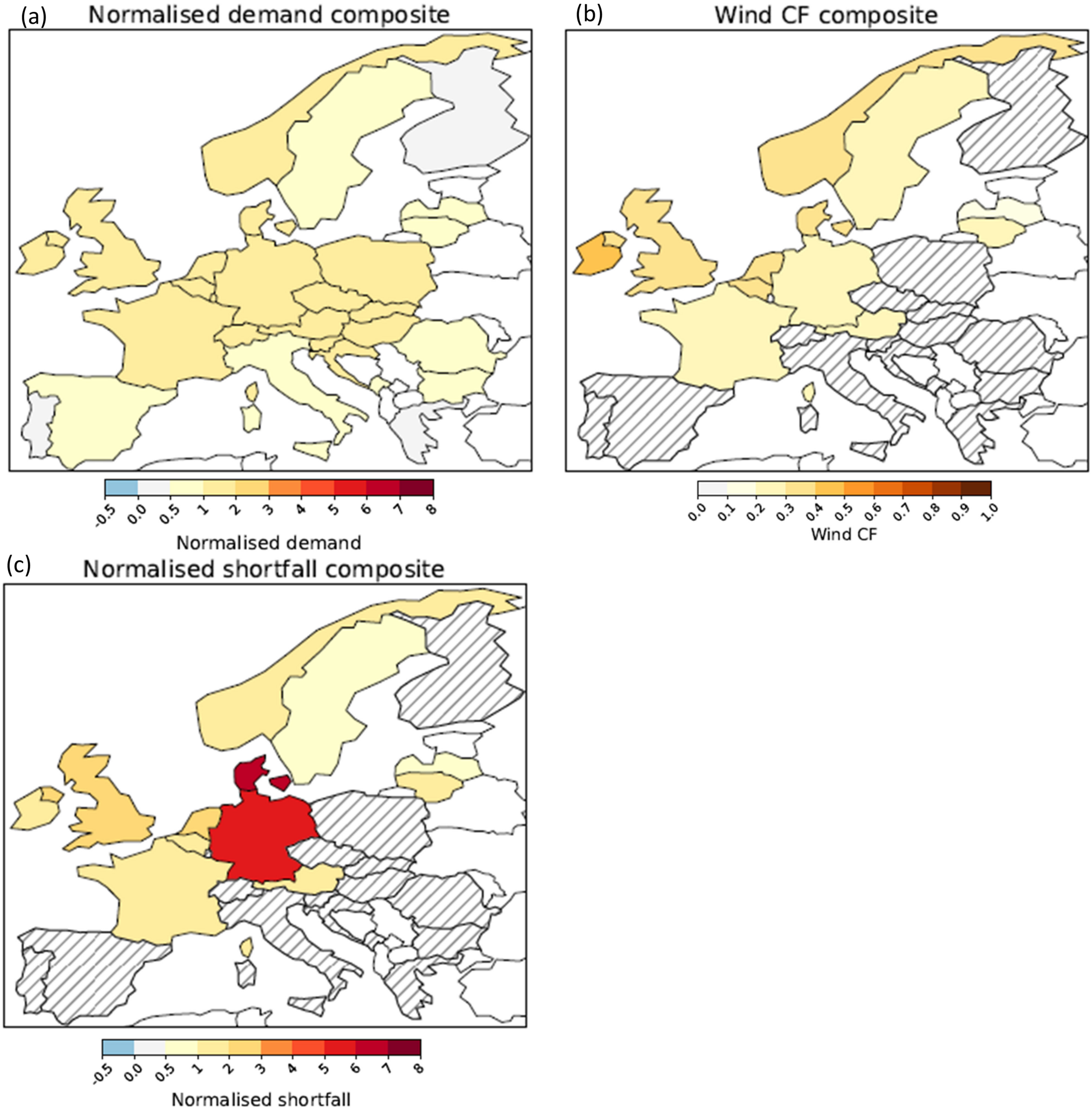

FIGURE 19 | DJF energy composite conditions. Energy demand (a); Wind CF (b); Energy shortfall (c). Stripes in (b) and (c) show countries for which wind CF and shortfall data are not available.

to study the impact of only the weather conditions on energy demand and supply. Compared to real-world energy data, this covers a significantly larger period, enabling the analysis of a large sample of weather conditions on the current energy network. In contrast to other studies which either focus on specific countries or on Europe as a whole, we here provide a general perspective across European countries but also highlight differences between countries and their causes. Following the investigation of weather regimes favouring shortfall days, we examine the possibility of simultaneous shortfall days for multiple countries. Additionally, we provide a perspective on a possible worst-case scenario over Europe, a recurrence of the cold winter of 1962–1963.

The first step consisted in identifying different types of extreme energy conditions, for which we considered demand and shortfall days which represent days with high demand and shortfall, respectively; and wind and solar drought days representing days with low wind and solar capacity factors, respectively. We identified a decreasing trend in demand, which is associated with the expected increase in wintertime temperatures (Figure 2). A long-term decrease in shortfall (given a fixed energy system) is, however, apparent for only about one-half of the countries. The difference in shortfall trend between countries is related to the relative dependence of shortfall to either demand or low wind conditions, which is apparent in the year-to-year variability as well as in the long-term trends. Countries with high installed wind capacity, or southern countries with warmer climates, have shortfall days that coincide more with wind days, while countries with low installed wind capacity, or northern countries with colder climates, have shortfall days that coincide more with demand days (Figures 5, 6). As countries will be increasing their proportion of renewable energy, and therefore installed wind capacity, the relative influence of high demand and low wind days on high shortfall days might, as a consequence, evolve (Bloomfield et al. 2018).

Investigating the characteristics of energy events (consecutive energy days) depending on their duration showed that longer shortfall events also had higher shortfall, which is linked to generally lower temperatures experienced during longer shortfall events (Figure 7). Thus, these events are particularly critical to the energy network. An interesting extension to this would be to investigate the capacity of forecasting models in representing these more persistent weather regimes, and therefore inform on the potential for more extreme shortfall situations.

In a second step, the influence of six weather regimes on the identified energy days was studied. A first important observation shows that some regimes, mostly blocking-type regimes (Atlantic Ridge, Scandinavian Blocking, negative North Atlantic Oscillation), favour the occurrence of shortfall days across most of Europe (Figure 12). Across the Mediterranean basin, shortfall days are favoured during the Scandinavian Trough regime (Figure 12). These results are consistent with previous studies (Bloomfield et al. 2020a; Grams et al. 2017; van der Wiel, Stoop, et al. 2019; Otero et al. 2022). Further analysis showed that some regimes affect multiple countries over large parts of Europe, suggesting that shortfall days can occur simultaneously for multiple countries, putting many national energy networks under stress. By further investigating this hypothesis, this paper shows that if countries that are part of a Regional Security Coordinator experience coinciding shortfall days, the closest neighbouring countries are likely to also experience shortfall days at the same time (Figures 13 and 14). This underlines that, while increasing connections with neighbouring countries is generally beneficial, extending these connections to more distant countries and increasing energy storage capacity would help mitigate these scenarios. Again, these scenarios are favoured by blocking-type regimes (Figures 15 and 16). A similar approach by Otero et al. (2022) highlighted the importance of blocking-type regimes for synchronous shortfall.

Finally, a case study was performed looking at the coldest winter of the 20th century in Europe. The aim is to examine the effect of a winter characterised by extremely persistent blocking regimes (Hirschi and Sinha 2007; Greatbatch et al. 2015) on the current energy network. We show that most European countries would experience higher than normal demand and shortfall, with an increased frequency of both demand and shortfall days for all countries (Figure 19). Similar winters are unlikely but not impossible (Sippel et al. 2024), an energy network more reliant on renewable energy sources needs to be prepared to weather these possible situations.

This study highlights how weather regimes impact countries differently, but also how their characteristic large spatial scale and temporal persistence can put large parts of Europe's energy network under intense strain. Furthermore, this puts further emphasis on the decision of the European Union to prioritise the expansion of energy connectivity across Europe through 'European electricity highways' for instance (European Commission 2010). The increased inter-connectivity aims to ensure security of supply but also better integration of renewable energy. This includes connections beyond the borders of Europe (European Commission 2013).

Author Contributions

Emmanuel Rouges: conceptualization, investigation, methodology, validation, formal analysis, writing – original draft, visualization, writing – review and editing. **Marlene Kretschmer:** conceptualization, writing – review and editing, supervision, investigation. **Theodore G. Shepherd:** conceptualization, investigation, writing – review and editing, supervision.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study. The ERA5 reanalysis (Hersbach et al. 2020) dataset used is freely available through the Copernicus Climate Change Service Climate Data Store. The energy dataset was produced by Bloomfield et al. (2020b) and can be accessed here (https://researchdata.reading.ac.uk/272/).

References

Beating the European Energy Crisis. 2022. IMF. https://www.imf.org/en/Publications/fandd/issues/2022/12/beating-the-european-energy-crisis-Zettelmeyer.

Bloomfield, H. C., and D. J. Brayshaw. 2021. *ERA5 Derived Time Series of European Aggregated Surface Weather Variables, Wind Power, and Solar Power Capacity Factors: Hourly Data From 1950-2020*. University of Reading. Dataset. https://doi.org/10.17864/1947.000321.

Bloomfield, H. C., D. J. Brayshaw, and A. J. Charlton-Perez. 2020a. "Characterizing the Winter Meteorological Drivers of the European Electricity System Using Targeted Circulation Types." *Meteorological Applications* 27, no. 1. https://doi.org/10.1002/met.1858.

Bloomfield, H. C., D. J. Brayshaw, and A. J. Charlton-Perez. 2020b. *ERA5 Derived Time Series of European Country-Aggregate Electricity Demand, Wind Power Generation and Solar Power Generation: Hourly Data From 1979-2019*. University of Reading. Dataset. https://doi.org/10.17864/1947.272.

Bloomfield, H. C., D. J. Brayshaw, P. L. M. Gonzalez, et al. 2021. "Sub-Seasonal Forecasts of Demand and Wind Power and Solar Power Generation for 28 European Countries." *Earth System Science Data* 13. https://doi.org/10.5194/essd-13.

Bloomfield, H. C., D. J. Brayshaw, L. C. Shaffrey, P. J. Coker, and H. E. Thornton. 2016. "Quantifying the Increasing Sensitivity of Power Systems to Climate Variability." *Environmental Research Letters* 11, no. 12: 124025.

Bloomfield, H. C., D. J. Brayshaw, L. C. Shaffrey, P. J. Coker, and H. E. Thornton. 2018. "The Changing Sensitivity of Power Systems to Meteorological Drivers: A Case Study of Great Britain." *Environmental Research Letters* 13, no. 5: 054028. https://doi.org/10.1088/1748-9326/aabff9.

Cassou, C., L. Terray, J. W. Hurrell, and C. Deser. 2004. "North Atlantic Winter Climate Regimes: Spatial Asymmetry, Stationarity With Time, and Oceanic Forcing." *Journal of Climate* 17, no. 5: 1055–1068. https://doi.org/10.1175/1520-0442(2004)017<1055:NAWCRS>2.0.CO;2.

Cassou, C., L. Terray, and A. S. Phillips. 2005. "Tropical Atlantic Influence on European Heat Waves." *Journal of Climate* 18, no. 15: 2805–2811. https://doi.org/10.1175/JCLI3506.1.

Dee, D. P., S. M. Uppala, A. J. Simmons, et al. 2011. "The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System." *Quarterly Journal of the Royal Meteorological Society* 137: 553–597. https://doi.org/10.1002/qj.828.

Dunnett, S., A. Sorichetta, G. Taylor, and F. Eigenbrod. 2020. "Harmonised Global Datasets of Wind and Solar Farm Locations and Power." *Scientific Data* 7, no. 1: 130.

Eichler, W. 1971. "Strenge Winter 1962/1963 und seine vielschichtigen biologischen Auswirkungen in Mitteleuropa." Verhandlungen der Zoologisch-Botanischen Gesellschaft in Wien.

Electricity Interconnection Targets. n.d. Energy. https://energy.ec.europa.eu/topics/infrastructure/electricity-interconnection-targets_en#:~:text=Connecting%20Europe's%20electricity%20systems%20will,import%20the%20electricity%20they%20need.f.

ENTSO. 2009. ENTSO-e at a Glance. https://eepublicdownloads.entsoe.eu/clean-documents/Publications/ENTSO-E%20general%20publications/entsoe_at_a_glance_2015_web.pdf.

ENTSO. 2019. European Network of Transmission System Operators for Electricity: Data Platform. https://www.entsoe.eu/data/transparency-platform/.

European Commission. 2010. Energy Infrastructure: Commission Proposes EU Priority Corridors for Power Grids and Gas Pipelines. https://ec.europa.eu/commission/presscorner/detail/en/IP_10_1512.

European Commission. 2013. Commission Delegated Regulation (EU) No 1391/2013. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R1391&from=EN.

European Commission. 2019. The European Green Deal. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF.

European Environment Agency. 2019. Adaptation Challenges and Opportunities for the European Energy System. https://www.eea.europa.eu/publications/adaptation-in-energy-system.

Falkena, S. K. J., J. de Wiljes, A. Weisheimer, and T. G. Shepherd. 2020. "Revisiting the Identification of Wintertime Atmospheric Circulation Regimes in the Euro-Atlantic Sector." *Quarterly Journal of the Royal Meteorological Society* 146, no. 731: 2801–2814. https://doi.org/10.1002/qj.3818.

Ferranti, L., S. Corti, and M. Janousek. 2015. "Flow-Dependent Verification of the ECMWF Ensemble Over the Euro-Atlantic Sector." *Quarterly Journal of the Royal Meteorological Society* 141, no. 688: 916–924.

Ferranti, L., L. Magnusson, F. Vitart, and D. S. Richardson. 2018. "How Far in Advance Can We Predict Changes in Large-Scale Flow Leading to Severe Cold Conditions Over Europe?" *Quarterly Journal of the Royal Meteorological Society* 144, no. 715: 1788–1802. https://doi.org/10.1002/qj.3341.

Grams, C. M., R. Beerli, S. Pfenninger, I. Staffell, and H. Wernli. 2017. "Balancing Europe's Wind-Power Output Through Spatial Deployment Informed by Weather Regimes." *Nature Climate Change* 7, no. 8: 557–562. https://doi.org/10.1038/NCLIMATE3338.

Greatbatch, R. J., G. Gollan, T. Jung, and T. Kunz. 2015. "Tropical Origin of the Severe European Winter of 1962/1963." *Quarterly Journal of the Royal Meteorological Society* 141, no. 686: 153–165. https://doi.org/10.1002/qj.2346.

Gutiérrez, C., M. Molina, M. Ortega, N. López-Franca, and E. Sánchez. 2024. "Low-Wind Climatology (1979–2018) Over Europe From ERA5 Reanalysis." *Climate Dynamics* 62: 1–4170.

Hannachi, A., D. M. Straus, C. L. E. Franzke, S. Corti, and T. Woollings. 2017. "Low-Frequency Nonlinearity and Regime Behavior in the Northern Hemisphere Extratropical Atmosphere." *Reviews of Geophysics* 55, no. 1: 199–234. https://doi.org/10.1002/2015RG000509.

Herrera-Lormendez, P., H. Douville, and J. Matschullat. 2023. "European Summer Synoptic Circulations and Their Observed 2022 and Projected Influence on Hot Extremes and Dry Spells." *Geophysical Research Letters* 50: e2023GL104580. https://doi.org/10.1029/2023GL104580.

Hersbach, H., B. Bell, P. Berrisford, et al. 2020. "The ERA5 Global Reanalysis." *Quarterly Journal of the Royal Meteorological Society* 146, no. 730: 1999–2049. https://doi.org/10.1002/qj.3803.

Hirschi, J. J.-M., and B. Sinha. 2007. "Negative NAO and Cold Eurasian Winters: How Exceptional Was the Winter of 1962/1963?" *Weather* 62: 43–48. https://doi.org/10.1002/wea.34.

Hiver 1962–63. n.d. Hiver 1962–63: Persistence de Grands Froids Pendant Trois Mois Accessed March 8, 2024. https://www.alertes-meteo.com/vague_de_froid/62-63/1962.htm.

INSEE. 2021. Population Changes – Demographic Balance Sheet 2021. https://www.insee.fr/en/statistiques/6040011?sommaire=6323335.

Kingsley, T. 2022. National Grid Blackouts 2022: What to Expect and Who Would Be Exempt? The Independent, November 24, 2022. https://www.independent.co.uk/news/uk/home-news/national-grid-blackouts-uk-winter-2022-b2232080.html.

Laurila, T. K., V. A. Sinclair, and H. Gregow. 2021. "Climatology, Variability, and Trends in Near-Surface Wind Speeds Over the North Atlantic and Europe During 1979–2018 Based on ERA5." *International Journal of Climatology* 41, no. 4: 2253–2278.

Lawson, A., and A. Voce. 2023. Energy Mix: How Is Electricity Generated in Great Britain? The Guardian. https://www.theguardian.com/environment/2023/feb/07/energy-dashboard-how-electricity-generated-great-britain.

Martínez-García, M., C. Ramos-Carvajal, and Á. Cámara. 2023. "Consequences of the Energy Measures Derived From the War in Ukraine on the Level of Prices of EU Countries." *Resources Policy* 86: 104114. https://doi.org/10.1016/j.resourpol.2023.104114.

Matsueda, M. 2011. "Predictability of Euro-Russian Blocking in Summer of 2010." *Geophysical Research Letters* 38, no. 6. https://doi.org/10.1029/2010GL046557.

Member companies. n.d. ENTSO-E Member Companies Accessed November 5, 2023. https://www.entsoe.eu/about/inside-entsoe/members/.

Michel, C., and G. Rivière. 2011. "The Link Between Rossby Wave Breakings and Weather Regime Transitions." *Journal of the Atmospheric Sciences* 68, no. 8: 1730–1748. https://doi.org/10.1175/2011JAS3635.1.

Michelangeli, P., R. Vautard, and B. Legras. 1995. "Weather Regimes: Recurrence and Quasi Stationarity." *Journal of Atmospheric Sciences* 52, no. 8: 1237–1256. https://doi.org/10.1175/1520-0469(1995)052<1237:WRRAQS>2.0.CO;2.

Mockert, F., C. M. Grams, T. Brown, and F. Neumann. 2023. "Meteorological Conditions During Periods of Low Wind Speed and Insolation in Germany: The Role of Weather Regimes." *Meteorological Applications* 30, no. 4: e2141. https://doi.org/10.1002/met.2141.

Molina, M. O., C. Gutiérrez, and E. Sánchez. 2021. "Comparison of ERA5 Surface Wind Speed Climatologies Over Europe With Observations From the HadISD Dataset." *International Journal of Climatology* 41, no. 10: 4864–4878.

Osman, M., R. Beerli, D. Büeler, and C. M. Grams. 2023. "Multi-Model Assessment of Sub-Seasonal Predictive Skill for Year-Round Atlantic–European Weather Regimes." *Quarterly Journal of the Royal Meteorological Society* 149, no. 755: 2386–2408. https://doi.org/10.1002/qj.4512.

Otero, N., O. Martius, S. Allen, H. Bloomfield, and B. Schaefli. 2022. "Characterizing Renewable Energy Compound Events Across Europe Using a Logistic Regression-Based Approach." *Meteorological Applications* 29, no. 5. https://doi.org/10.1002/met.2089.

Power regions. 2022. Interconnected Europe. https://www.entsoe.eu/regions/.

Raynaud, D., B. Hingray, B. François, and J. D. Creutin. 2018. "Energy Droughts From Variable Renewable Energy Sources in European Climates." *Renewable Energy* 125: 578–589.

Shepherd, T. G. 2014. "Atmospheric Circulation as a Source of Uncertainty in Climate Change Projections." *Nature Geoscience* 7, no. 10: 703–708. https://doi.org/10.1038/ngeo2253.

Sippel, S., C. Barnes, C. Cadiou, et al. 2024. "Could an Extremely Cold Central European Winter Such as 1963 Happen Again Despite Climate Change?" *Weather and Climate Dynamics* 5: 943–957.

Stowell, D., J. Kelly, D. Tanner, et al. 2020. "A Harmonised, High-Coverage, Open Dataset of Solar Photovoltaic Installations in the UK." *Scientific Data* 7, no. 1: 394.

Straus, D. M., S. Corti, and F. Molteni. 2007. "Circulation Regimes: Chaotic Variability Versus SST-Forced Predictability." *Journal of Climate* 20, no. 10: 2251–2272. https://doi.org/10.1175/JCLI4070.1.

Thornton, H. E., A. A. Scaife, B. J. Hoskins, and D. J. Brayshaw. 2017. "The Relationship Between Wind Power, Electricity Demand and Winter Weather Patterns in Great Britain." *Environmental Research Letters* 12, no. 6: 064017. https://doi.org/10.1088/1748-9326/aa69c6.

Torriti, J. 2017. "The Risk of Residential Peak Electricity Demand: A Comparison of Five European Countries." *Energies* 10, no. 3: 385. https://doi.org/10.3390/en10030385.

van der Wiel, K., H. C. Bloomfield, R. W. Lee, et al. 2019. "The Influence of Weather Regimes on European Renewable Energy Production and Demand." *Environmental Research Letters* 14, no. 9: 094010. https://doi.org/10.1088/1748-9326/ab38d3.

van der Wiel, K., L. P. Stoop, B. R. H. van Zuijlen, R. Blackport, M. A. van den Broek, and F. M. Selten. 2019. "Meteorological Conditions Leading to Extreme Low Variable Renewable Energy Production and Extreme High Energy Shortfall." *Renewable and Sustainable Energy Reviews* 111: 261–275. https://doi.org/10.1016/j.rser.2019.04.065.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supplementary Figures.