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 one of the necessary steps 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 energy production. Identifying periods of high shortfall, here defined as when demand exceeds production by renewables, and how these periods are affected by weather, is therefore critical. We use a previously constructed energy dataset derived from reanalysis data for a fixed energy system to analyse the link between weather regimes and periods of high shortfall during the boreal winter for 28 European countries. For each country we identify days with critical energy conditions, focusing on those with high energy demand, low production from wind and, solar, and high energy shortfall. Only a subset of the here considered six North Atlantic weather regimes are found to favour the occurrence of high shortfall days. In particular, blocking-type regimes affect large parts of Europe and multiple countries, suggesting that high shortfall days can occur across multiple countries simultaneously. Furthermore, if a subset of countries experience shortfall days, neighbouring countries have a higher likelihood of also experiencing shortfall days. The impact of the coldest winter of the 20th century in Europe as a potential worst-case scenario is examined. It is found that the persistent blocking conditions associated with that winter, if they occurred today, would lead to high demand and shortfall across most of Europe during most of the winter.

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 et al., 2019a; 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) which 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.

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 (e.g. liquefied natural gas, energy imports, gas-fired power stations), leading to more volatile prices (Lawson & 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).

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 et al., 2019a), energy compound events (Otero et al., 2022), peak demand-net-renewables (Bloomfield et al., 2020a), and Dunkelflauten (Mockert et al., 2022). 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 in general (Grams et al., 2017; Thornton et al., 2017) and also for energy shortfall events (Mockert et al., 2022; van der Wiel et al., 2019b). 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). Weather regimes modulate surface weather (Cassou et al., 2004; Ferranti et al., 2018) and are associated with high impact weather 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 (e,g. temperature, wind, solar radiation) motivates studies on the use of weather regimes to inform deployment of wind farms (Grams et al., 2017), to understand the sensitivity of a renewable energy generation system (van der Wiel et al., 2019b) or to forecast renewable generation (Bloomfield et al., 2021).

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

This paper studies the characteristics of energy shortfall across 28 European countries during winter from a weather regime perspective. In particular, we quantify the relative influence of weather regimes for energy shortfall on individual countries and for shortfall that occurs in multiple countries simultaneously. Following this investigation, 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 1962/63), presenting a potential worst case scenario.

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-metre temperature (2mT), geopotential at 500 hPa (Z500), zonal (u10m) and meridional wind components (v10m) at 10-metres, 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 20N to 80N and 90W to 60E at 1 degree horizontal resolution. From the wind components the horizontal wind at 10-metres (W10m) is computed:

$$W10m = \sqrt{u10m^2 + v10m^2}$$

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.

The energy dataset from Bloomfield et al. (2020b) is used to quantify the energy conditions. This dataset contains energy demand, as well as the capacity factor (CF) of both wind and solar data derived from ERA5 at hourly resolution. The CF is defined as the ratio of actual generated wind or solar energy to the installed capacity. This dataset has the benefit of covering a long period from 1979 to 2019 for 28 different European countries (see Figure 4). For the calculation of energy variables, human factors such as energy infrastructure and the socio-economic conditions (e.g. demography, behaviour) are set to the 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 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. This allows to identify periods where the population is likely to use heating (Heating Degree Days: HDD) or air conditioning (Cooling Degree Days: CDD), therefore influencing the energy demand. 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 which 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.

Wind CF is estimated using horizontal wind at 100m, as the hub height is assumed to be at 100m. Additionally, the location of wind farms 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 passed 25°C). However the distribution of solar photovoltaic capacity is assumed to be uniform as reliable information is not available as for wind farms.

A more comprehensive explanation of the model used to derive the energy data from the ERA5 data is provided in the supplementary material of Bloomfield et al. (2020a).

For better comparison with the daily meteorological data, the energy data is changed to daily values. For energy demand, the hourly demand is summed over the 24h 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 the 24 hours 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.

a. Energy days definition

The aim of the present study is to understand the relationship between weather regimes and shortfall. Shortfall is defined as the difference between energy demand and renewable energy generation, also known as residual load (van der Wiel et al., 2019).

The focus is on days with extreme energy conditions, which are called extreme 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: 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.

To discuss the effects of persistence, brief energy events are defined as those lasting 3 days or less, while long energy events are defined as those lasting 5 days or more. 4-day events are disregarded to ensure that the length of brief and long events are sufficiently different for comparison.

To highlight the effect of very persistent weather regimes, we analyse the cold winter of 1962-1963. As the energy dataset presented does not cover this winter, we use another available dataset covering the period from 1950 to 2020 (Bloomfield & Brayshaw, 2021). This dataset uses a similar methodology to the one used for the rest of the dataset but the demographic conditions and the positions of wind and solar farms are taken from 2020 and April 2021 respectively. Additionally, 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 is computed. For consistency, the energy days are computed using the percentile values from this dataset covering the period 1950-2020.

b. Weather regime computation

We compute weather regimes using the k-means clustering algorithm on Z500 anomaly data (Michelangeli et al., 1995; Hannachi et al., 2017; Falkena et al., 2020). Following recommendations by 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 to set the number k of clusters, and iteratively identifies the optimal partition of the data. The most used weather regime classification identifies four regimes (Michelangeli et al., 1995; Ferranti et al, 2014) but in recent years, new classifications have been proposed using seven regimes (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 any 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 & Rivière (2011). This time-series is then normalised and for each day the highest regime index is selected. In case 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.

3. Results

a. Characteristics of energy days

We first compute time-series of frequencies of energy days to analyse trends. Examples of France and Germany will be shown throughout as they well represent key groups of countries and their characteristics from an energy perspective. If further differences are found, they are shown or described.

While there is no significant trend in the frequency of both solar and wind drought days across all countries, demand days see a significant decrease in frequency for all countries (Figure 1a and c) at the 95 percent confidence level using a bootstrap resampling method. This decrease in frequency of demand days is highly anti-correlated with the increase in winter temperatures for each country (e.g. -0.7 and -0.8 for France and Germany respectively), suggesting it being related to climate change.

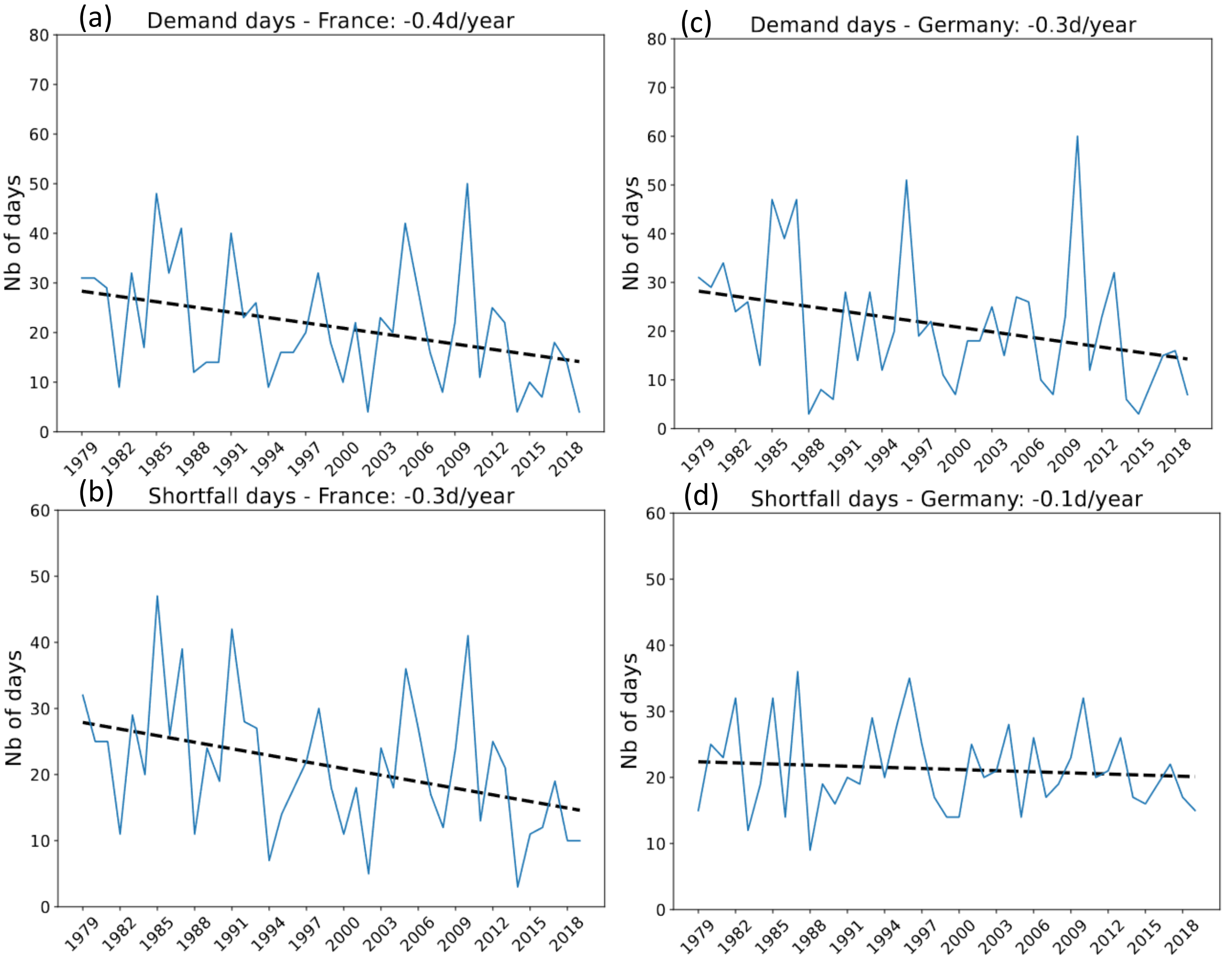


Figure 1: Yearly frequency of demand and shortfall days during the period 1979 – 2019 for France (a and b) and Germany (c and d). Dotted line shows the associated linear trend. The value shows the slope of the linear trend in days per year

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 meteorology, 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 (Figure 1b and d), however the magnitude of the decrease compared to that of demand days varies across countries. Both France and Germany have a similar trend of decreasing frequency of demand days. However, the decrease in shortfall days is much higher in France (-0.4 days/year) than in Germany (-0.1 day/year, Figure 1). This difference can be explained by the difference in installed wind capacity between the two countries; countries with higher wind capacity (e.g. Germany) have a weaker decreasing trend in shortfall than countries with lower wind capacity (e.g. France), because in the former case, as will be shown in more detail further below, shortfall is determined by wind as well as by temperature and thus is less sensitive to changes in temperature.

The distribution in frequency of energy days during each month of the cold season (Figure 2) is linked to the climatology of weather conditions that affect the particular energy variable. For instance, energy demand days (Figure 2a and e) are most frequent during the winter months (December, January, February; DJF) and less in the transition months (October, November, March, April), as DJF corresponds to the colder months of the year. Similarly, most solar drought days occur in DJF (Figure 2c and g) as daylight is reduced. For wind drought days (Figure 2b and f), the distinction is less clear but generally DJF is associated with stormier conditions and hence stronger winds. Therefore most wind drought days occur during the transition months.

Differences between countries further arise when looking at seasonal frequency variations of shortfall days (Figure 2d and h). Shortfall days are dependent on a combination of energy demand and renewable generation, and therefore the distribution across months is less straightforward than for demand days. In particular, countries with high installed wind capacity such as Germany (Figure 2h) have a broader distribution of shortfall days compared to countries with lower installed wind capacity such as France (Figure 2d).

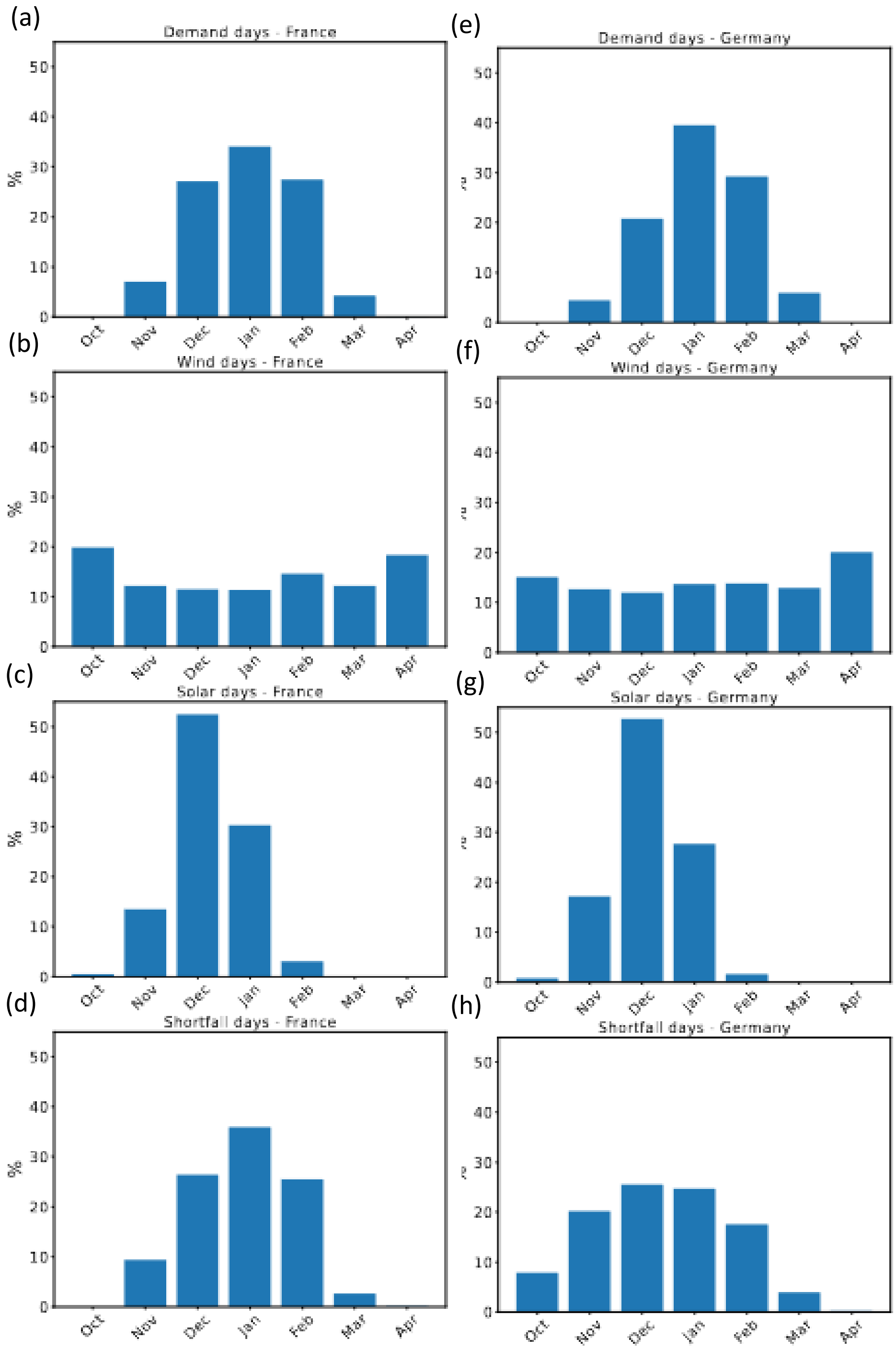


Figure 2: Frequency of energy days during each month for France (a - d) and Germany (e - h).

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 3. It appears that for 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 3a and 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 3c and d).

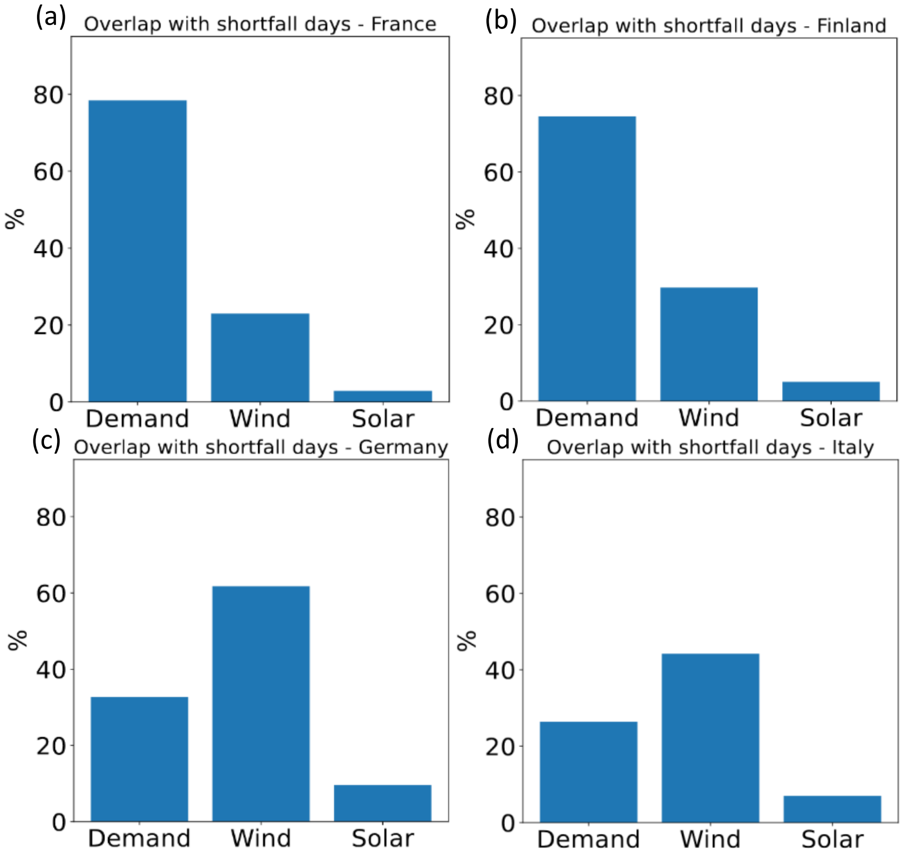


Figure 3: Percentage of shortfall days coinciding with high demand, low wind and solar days for France, Finland, Germany and Italy.

Figure 4 shows which countries have shortfall days that mainly coincide with demand or wind drought days together with the respective percentages. This shows that the general rule works most of the time with some exceptions such as Lithuania and Poland.

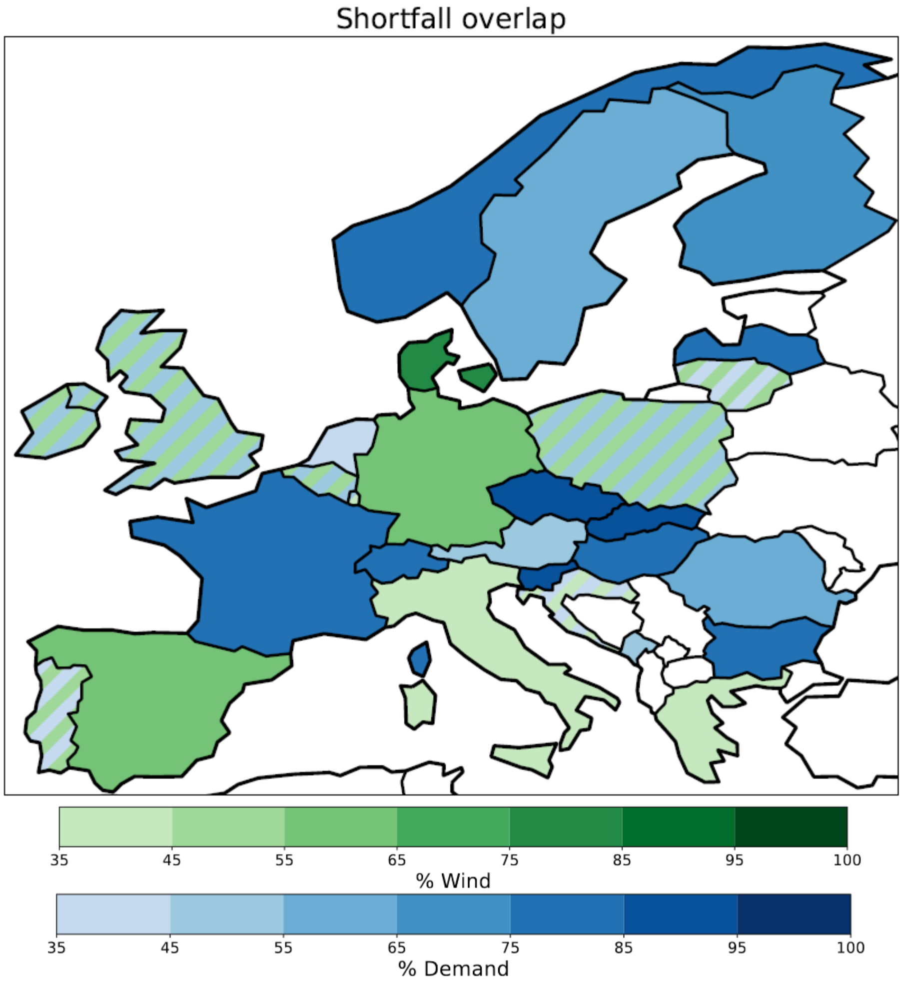


Figure 4: Percentage of wind days (for countries whose shortfall days overlap most with wind days) or demand days (for countries whose shortfall days overlap most with demand days) coinciding with shortfall days. Stripes show countries for which the percentage of shortfall days overlapping with wind or demand days is within 10%.

We next investigate if the duration of energy events (that is, consecutive energy days) affects the intensity of energy events. For this comparison, Figure 5 looks at the average and maximum shortfall values during brief and long shortfall events in France and Germany. The average and maximum shortfall values are higher during long shortfall events (the differences are however not statistically significant). Similarly, demand values are higher and wind CF is lower during long shortfall events (not shown). While only France and Germany are shown here, this observation is applicable to other countries as well. It is speculated that this could be due to the build-up of cold air masses leading to higher demand and therefore higher shortfall.

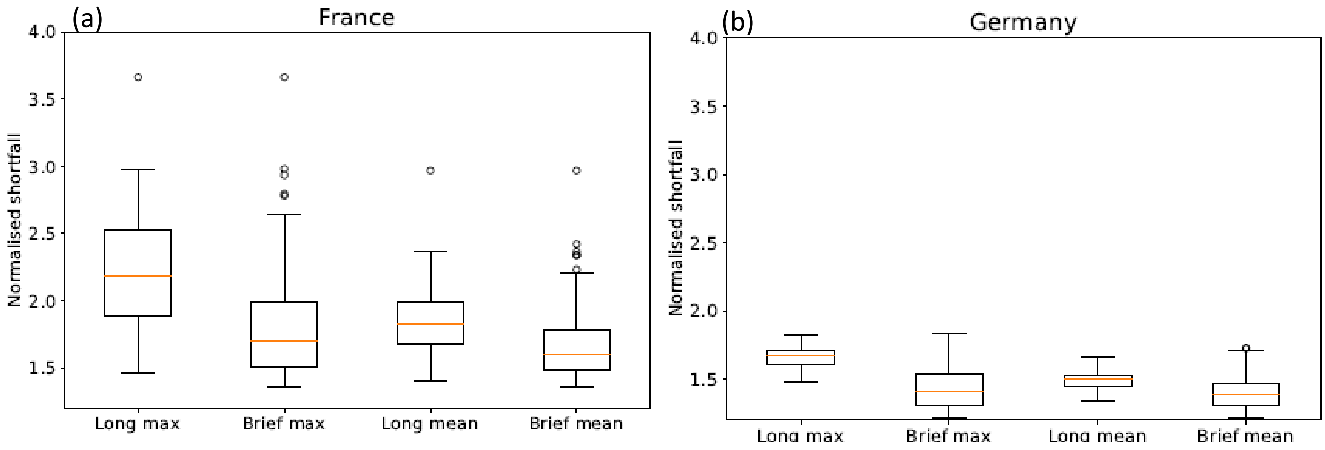
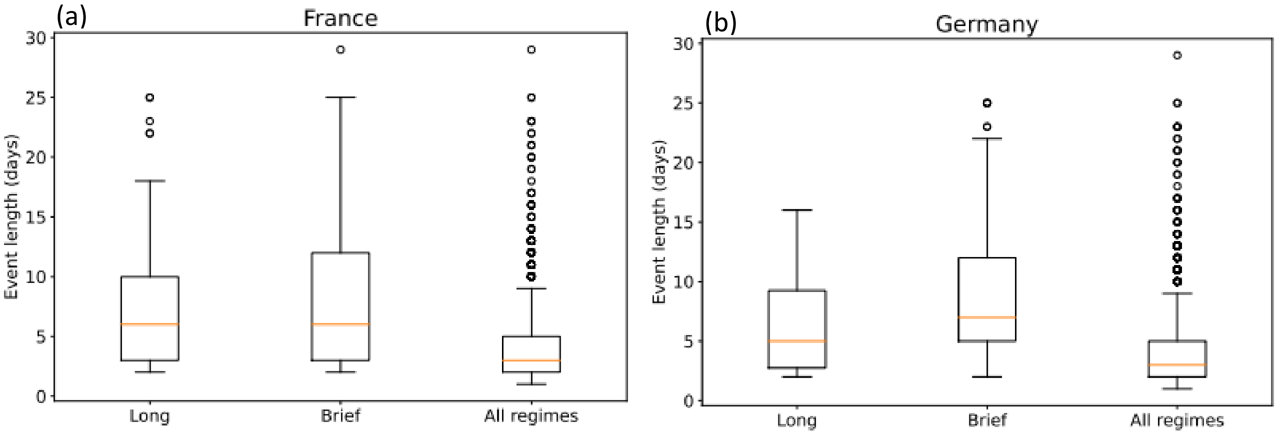


Figure 5: Boxplot showing the maximum and mean shortfall values for brief and long shortfall events for France (a) and Germany (b). The box represents the 25th and 75th percentile range, while the orange line shows the median value. Whiskers show the 10th to 90th percentile range while the circles show outliers.

Figure 6 investigates whether the duration of shortfall events is due to differences in the persistence of weather regimes. This shows that weather regimes are more persistent during shortfall events compared to the average persistence of all weather regimes. However, the duration of shortfall events does not appear to be affected by weather regime persistence. The analysis nevertheless suggests that the persistence of weather regimes is key for the occurrence of shortfall events.



b. Surface impacts of weather regimes

Figure 6: Persistence of all weather regimes, during long or brief shortfall events and all regimes for France (a) and Germany (b).

Before analysing the links between weather regimes and energy events, we describe their imprint on European weather. 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 7 presents the Z500 absolute and anomaly composites of all six regimes. It appears that the AtTr can be characterised as the polar opposite of the AtR with a cyclonic anomaly over the British Isles, where one would expect an anticyclonic anomaly during the AtR. The additional regime splits 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 anticyclonic anomaly over northern Europe. It is important to note the difference with the classical representation of the NAO+ as this also leads to different surface impacts, compared to what is generally understood. The additional regimes correspond to the Scandinavian Blocking negative (ScTr) and Atlantic Ridge negative (AtTr) from Falkena et al. (2023).

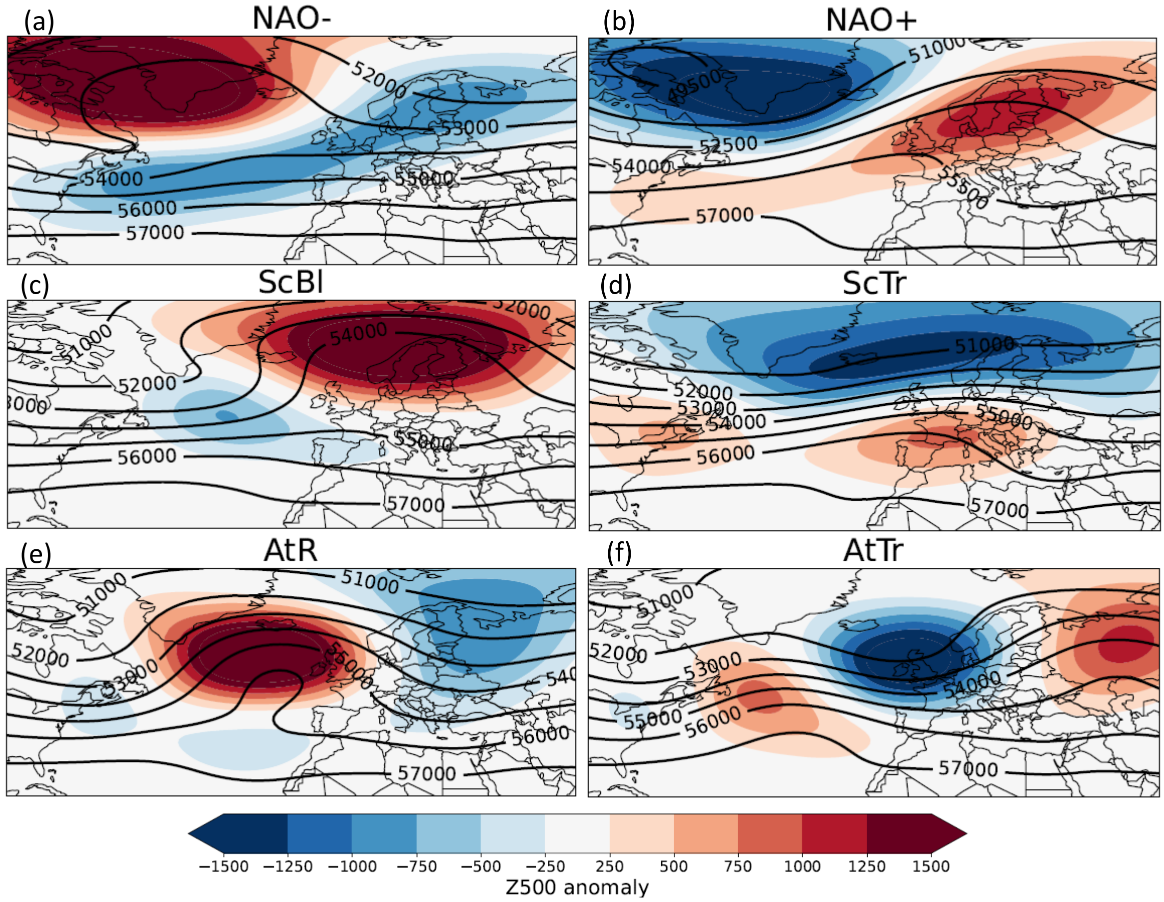


Figure 7: Composites of all six regimes: NAO- (a), NAO+ (b), ScBl (c), ScTr (d), AtR (e), AtTr (f). Colours show the Z500 anomaly and the contouring shows the Z500 absolute values.

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).

To understand the relative influence of the weather regimes on energy variables, we show the regime composites of 2mT (Figure 8), W10m (Figure 9) and ISR (Figure 10).

Cold temperatures across several countries are associated with the AtR, ScBl and NAO- regimes (Figure 8). The NAO- regime (Figure 8a) affects most of northern Europe with negative anomalies extending to southern Germany and northern France while temperatures reach close to 4 degrees below climatology over Scandinavia. The ScBl regime (Figure 8b) however 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 8c) cover all of Europe with strongest anomalies concentrated over continental Europe, from France to the Baltic countries.

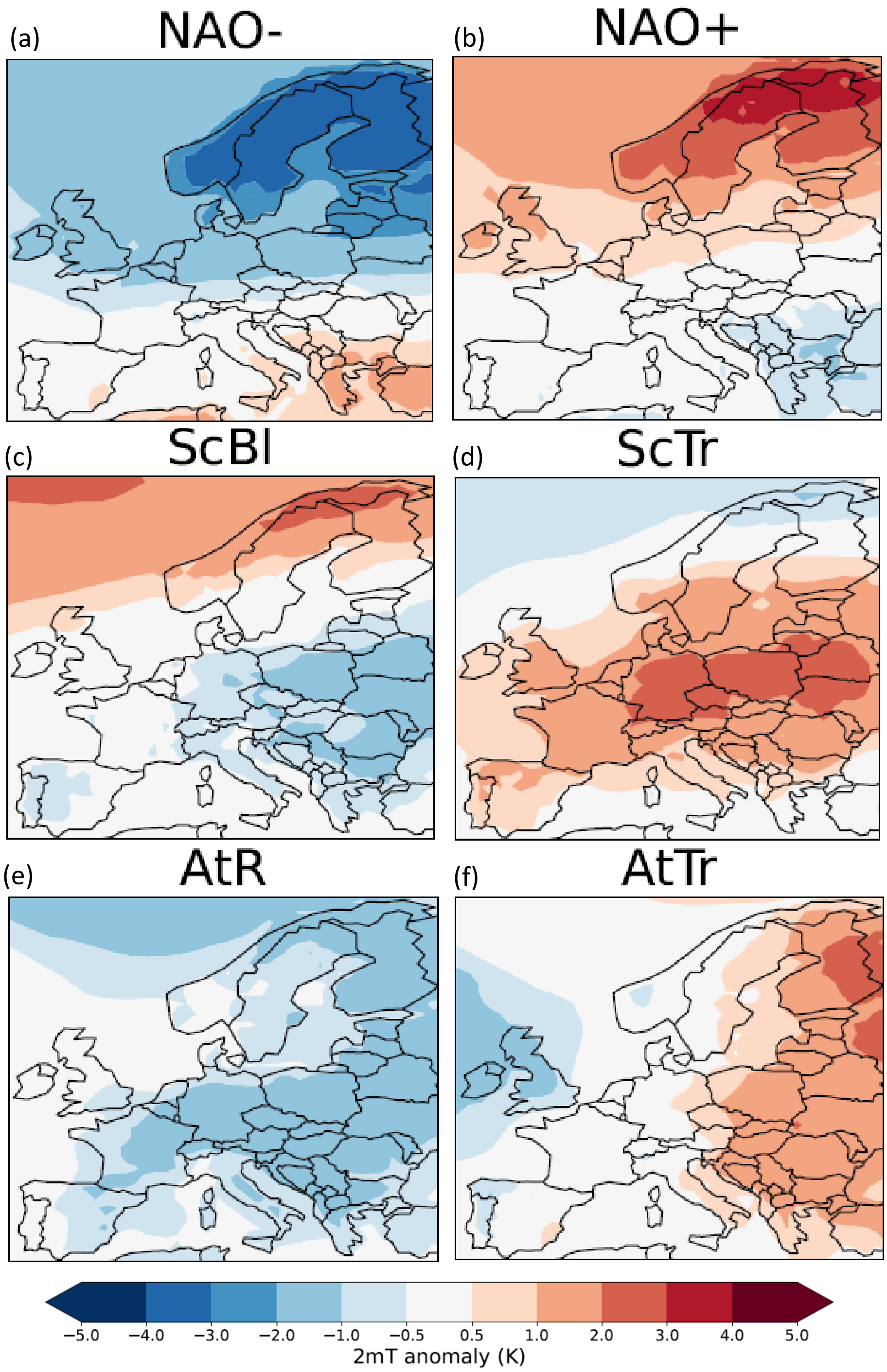
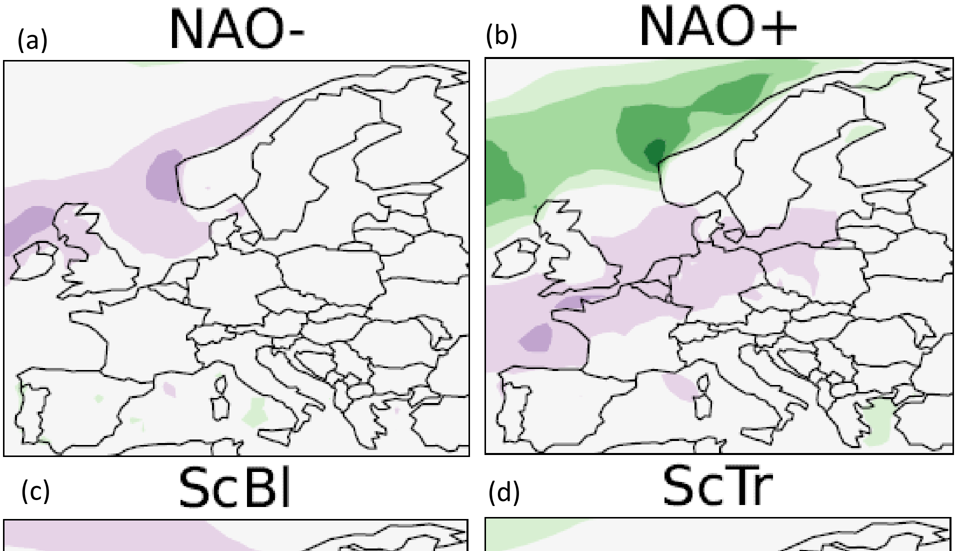


Figure 8: Composites of all six regimes: NAO- (a), NAO+ (b), ScBl (c), ScTr (d), AtR (e), AtTr (f). Colours show the 2mT anomaly.

These same regimes are associated with low wind conditions over some regions of Europe (Figure 9). The negative wind anomalies cover fewer countries but generally affect similar regions. These regimes (AtR, ScBl and NAO-) lead to lower wind conditions across northern Europe and the western coasts (Figure 9a, 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 9b and d), respectively.

Figure 9: Composites of all six regimes: NAO- (a), NAO+ (b), ScBl (c), ScTr (d), AtR (e), AtTr (f). Colours show the W10m anomaly.



Low solar conditions follow different patterns, however (Figure 10). The NAO- and AtTr regimes (Figure 10a and e) coincide with low solar conditions across most of Europe while the ScBl regime affects southern Europe (Figure 10c).

Solar conditions are less relevant during the winter compared to summer due to shorter periods of daylight. As the ScBl, NAO- and AtR regimes lead to both colder and lower wind conditions across large parts of Europe, these regimes are most likely to affect energy shortfall.

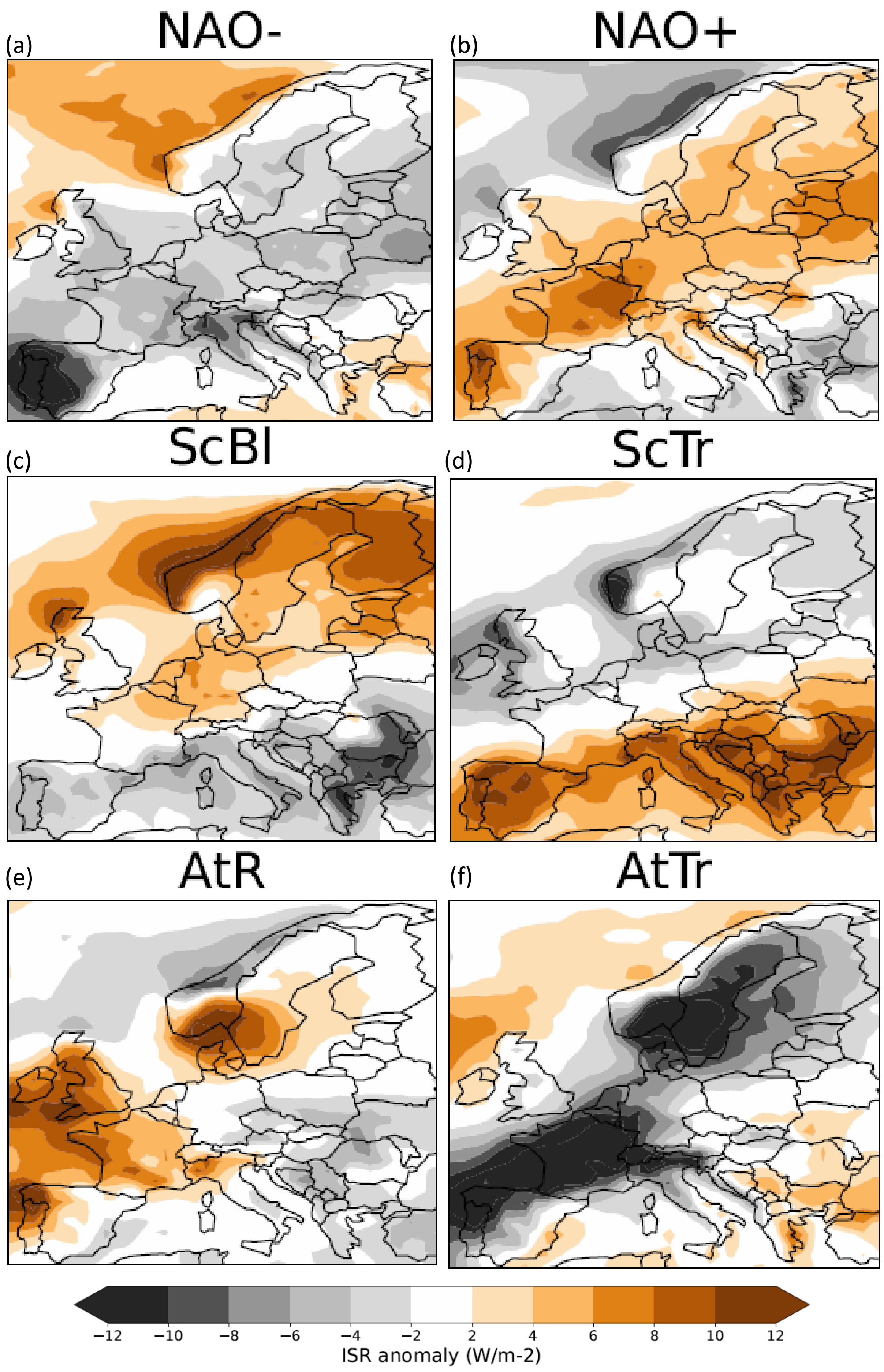


Figure 10: Composites of all six regimes: NAO- (a), NAO+ (b), ScBl (c), ScTr (d), AtR (e), AtTr (f). Colours show the ISR anomaly.

We next examine trends in the frequency of regimes (Figure 11). The ScTr and ScBl regimes show the highest frequency trend with a decrease of ~9 days and an increase of close to 18 days, respectively, in yearly frequency over the last four decades. However, only the ScBl regime shows a statistically significant trend at the 95% confidence level using a bootstrap resampling method. In the other classifications, the ScBl regime and the ScTr regime (NAO+ for the classical classification using only four regimes where the ScTr regime is not present) also have large trends (albeit being statistically not significant at the 95th confidence level). This information combined with the knowledge that ScBl regimes can lead to cold conditions suggests that conditions favouring high demand might have become more frequent in recent years, although as noted earlier there is a general decrease in high-demand conditions because of long-term warming.

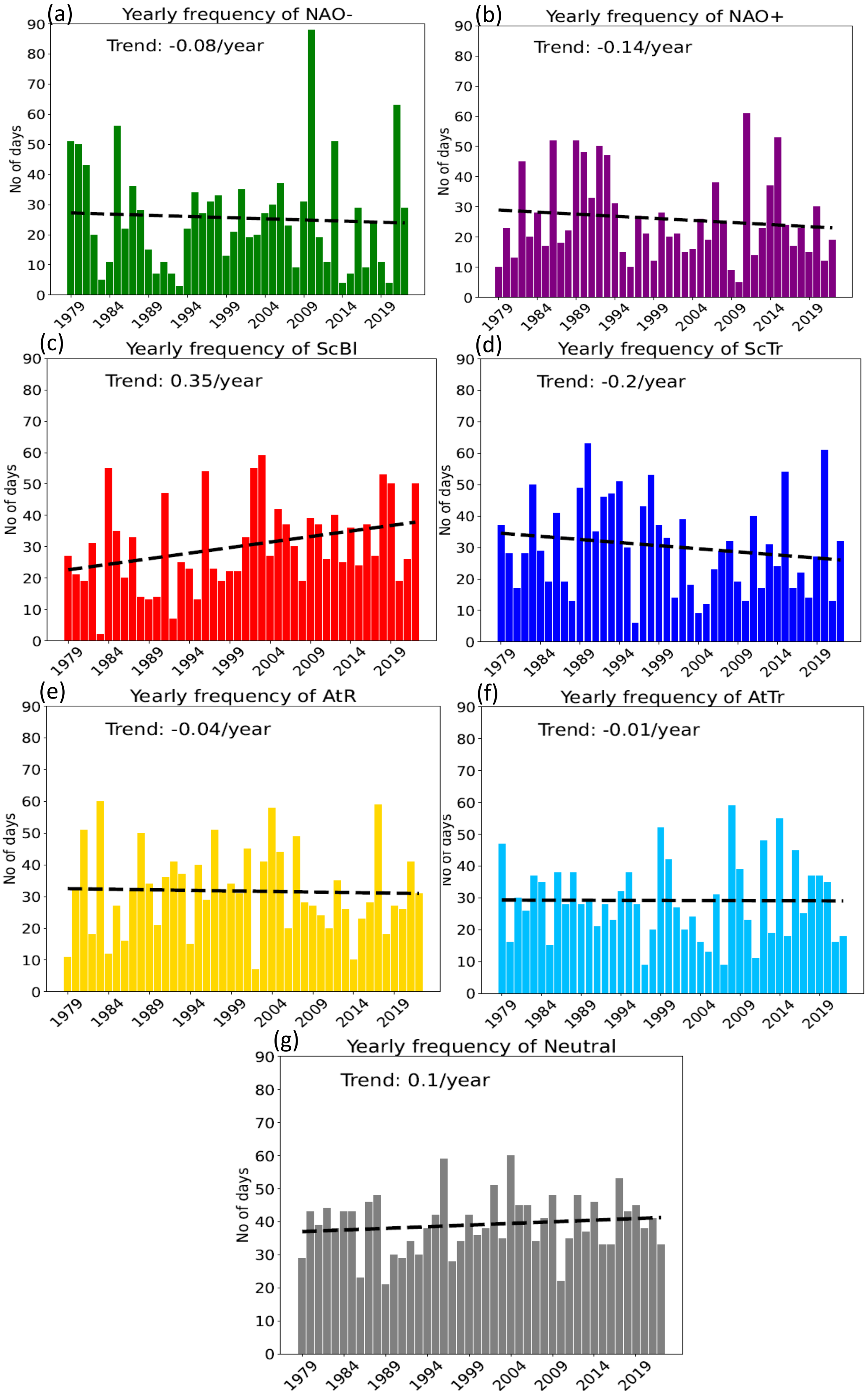


Figure 11: Yearly frequency of weather regimes during the period of 1979 - 2022. Dashed line shows the associated linear trend. The value shows the slope of the linear trend in days per year.

c. Influence of weather regimes on energy days

In the following section the relationship between weather regimes and energy, in particular energy days, is discussed.

i. Impact of weather regimes across Europe

In the following example, the energy distribution is shown during the different weather regimes for each energy variable for Germany (Figure 12a to d). Only the distribution of wind CF (Figure 12.b) 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, Figures 12e to h show the conditional probability of energy days during each regime, highlighting how some energy days are more probable during some regimes. For example, the ScBl and NAO- regimes are associated with demand days (Figure 12e). Thus, while the distribution alone is not helpful in distinguishing between different energy scenarios, it appears that the conditional probability of energy days helps to highlight which regimes are more likely to favour energy days.

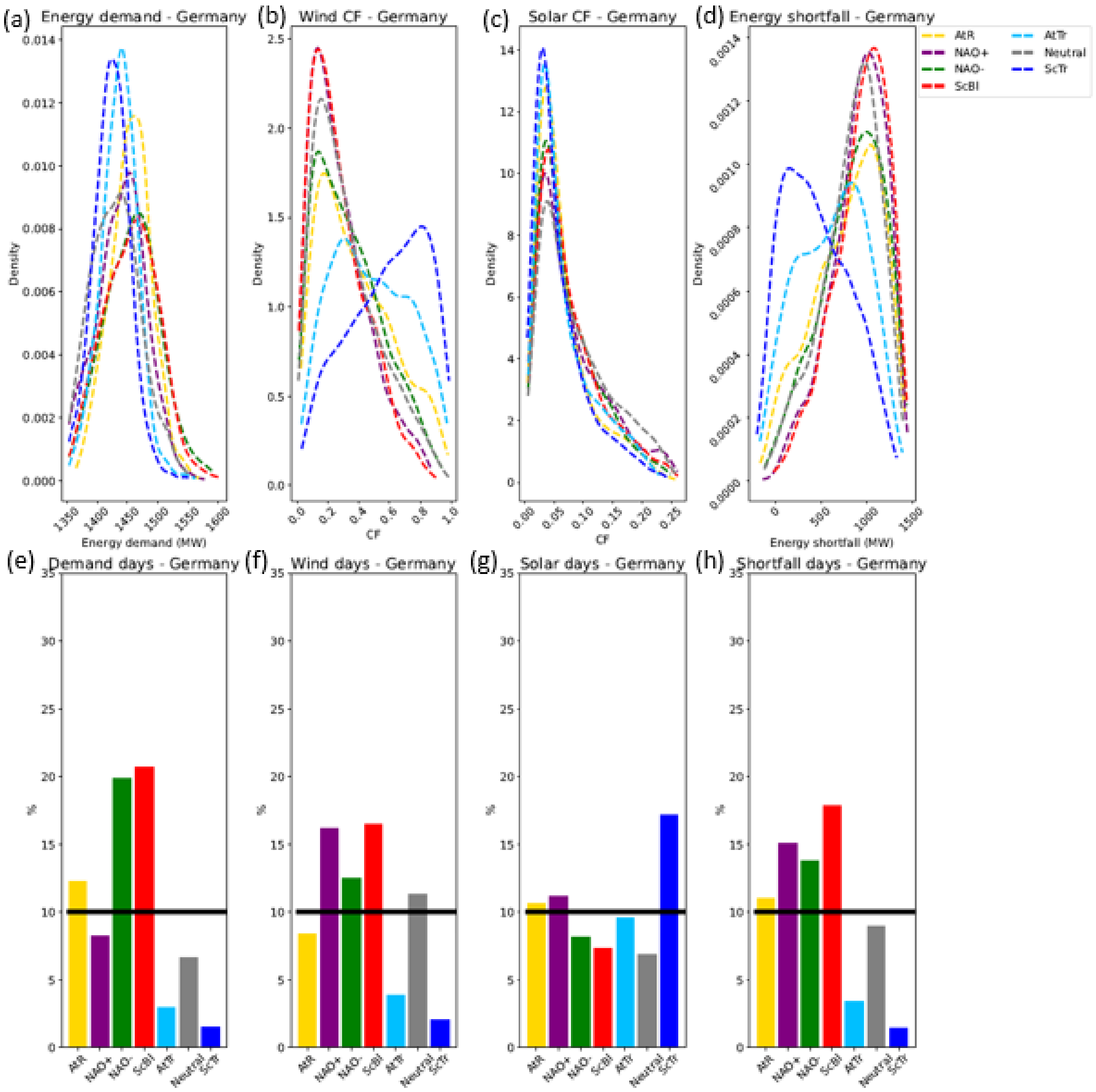


Figure 12: Energy distribution during each weather regime and each energy variable for Germany (a - d). Conditional probability of energy days during each weather regime (e - h). The black line shows the climatological probability of each energy day.

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 13).

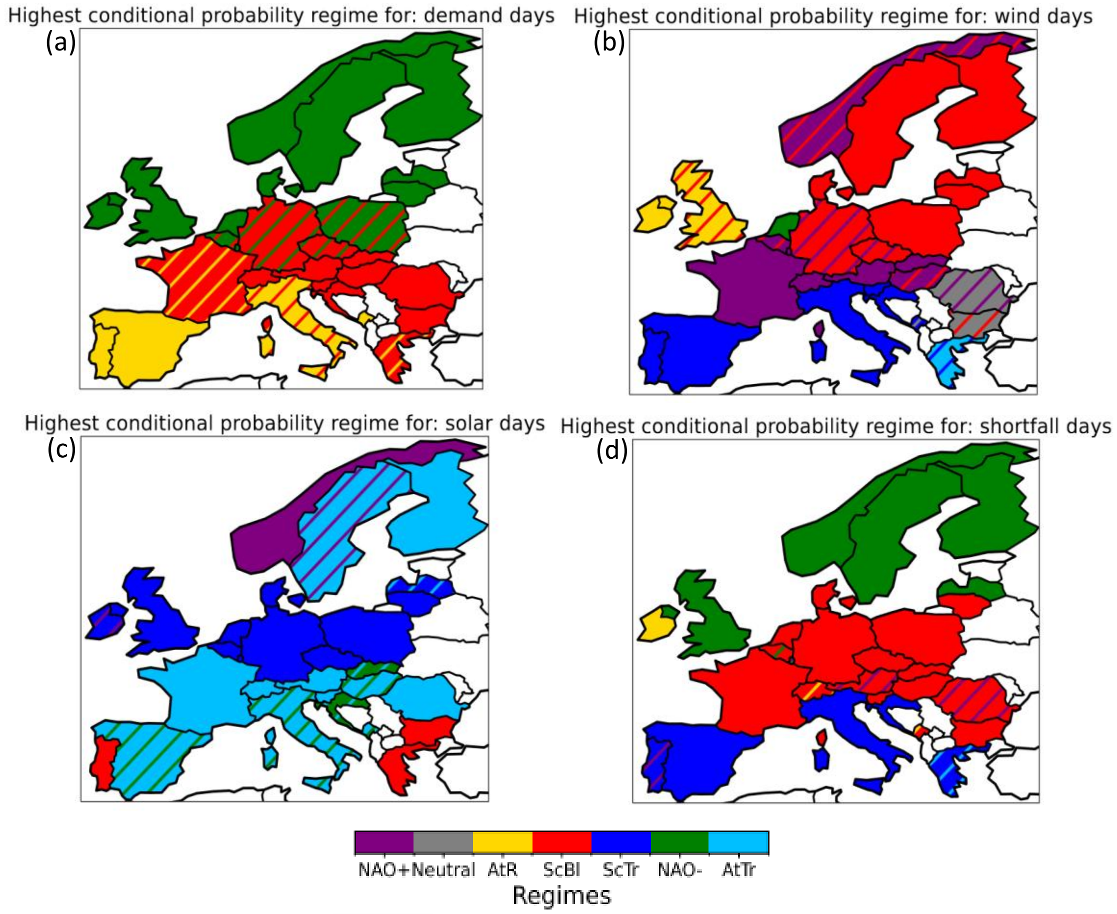


Figure 13: Shows regimes with the highest conditional probability of high demand (a), low wind (b), low solar (c) and high shortfall days (d) to occur. The stripes show also the regime with second highest conditional probability if it is within 2% of the highest.

When considering demand and shortfall days in particular (Figure 13a and d), Europe appears split. Scandinavia, Denmark, the British Isles and the Baltic countries all have the NAO- regime as the one with the highest conditional probability of high demand days to occur, while most of central Europe is dominated by the ScBl regime (Figure 13.a). Most Mediterranean countries and Portugal are more affected by the AtR regime. For shortfall days (Figure 13.d), it is a very similar situation 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). A notable difference is the European Blocking regime being more represented than the ScBl regime for high shortfall days for the classification with 7 regimes. Compared to the ScBl regime, the European Blocking regime's anticyclonic anomaly is centred more over the British Isles and not the Scandinavian region.

Figure 13 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.

ii. Connected countries

The TSOs 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. 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 the context of this study, the assumption is that countries within each RSC are well interconnected in their energy power systems. Therefore, if one country experiences shortfall, it can draw electric power from countries within the same RSC. However, if all countries or several within the RSC are experiencing a shortfall, this strategy might become difficult. Here, such common shortfall days, that is shortfall days that occur at the same time in all countries of the same RSC, are discussed.

The RSCs considered 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 will not be considered as data for only one of the countries (Montenegro) is available from the dataset used here.

Figure 14 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 and 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.

Figure 14: 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.

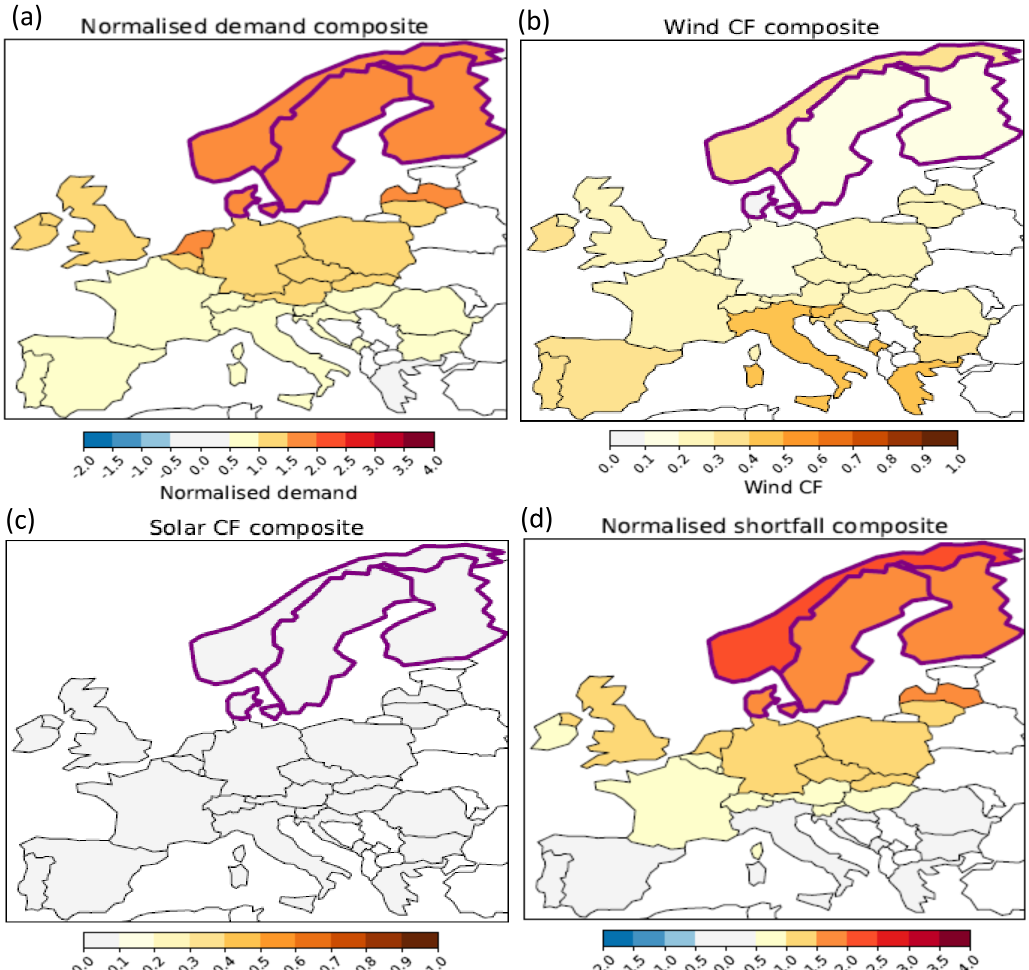


Figure 15 shows the percentage of common days for each RSC which overlap with shortfall days in countries outside each RSC. In the case of the Nordic RSC neighbouring countries are likely to experience a shortfall day at the same time as countries from the same RSC. However, countries which are further away and in particular south of the Alps and Pyrenees are less likely to experience a shortfall day at the same time.

These observations are applicable to other RSCs. In the case of RSCs (Nordic, SEleNe) where all countries are north or south of large mountain ranges, it appears that countries on the other side of the mountain range are less likely to experience shortfall days.

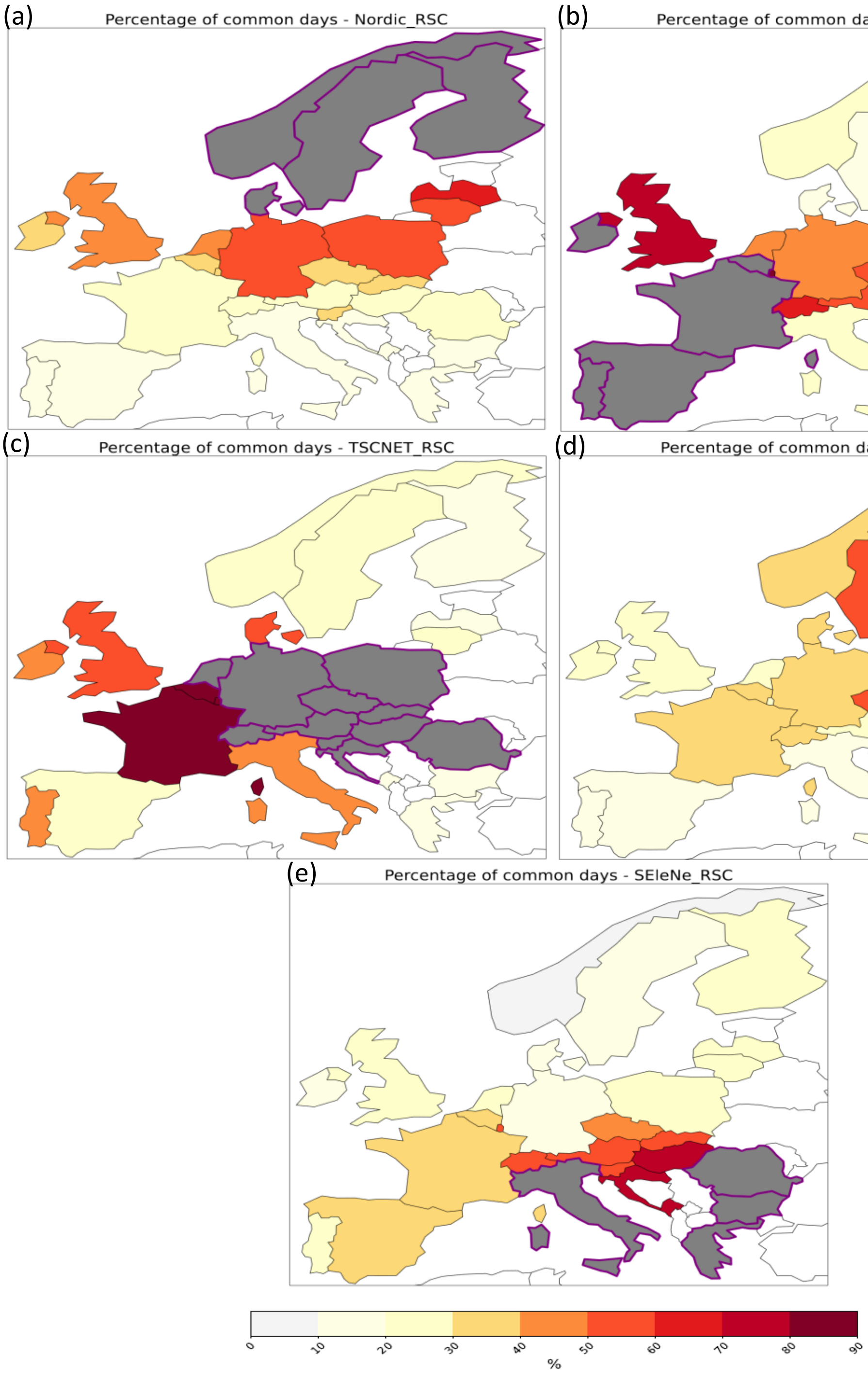
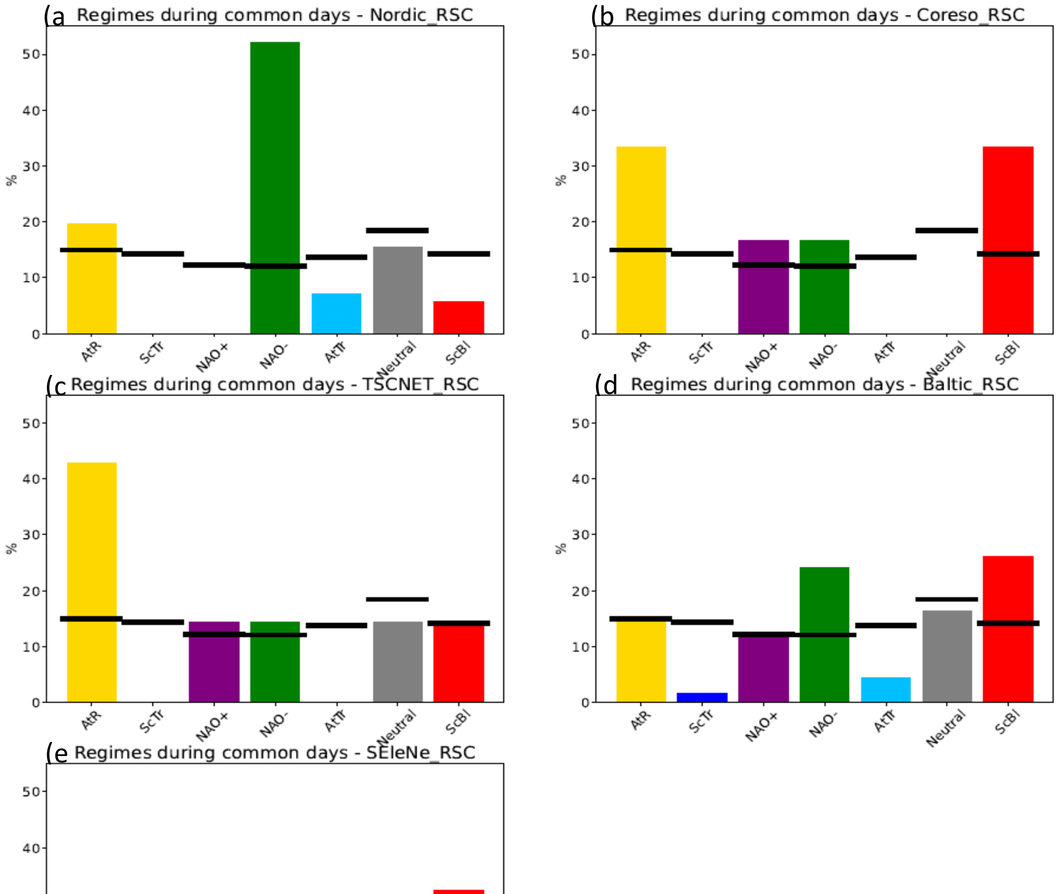


Figure 15: Percentage of shortfall days coinciding with common shortfall days of the Nordic, CORESO, TSCNET, Baltic and SEleNe RSC countries. Purple contours show the countries part of the same RSC. These countries are greyed out too, as the percentages are 100% for these countries by construction.

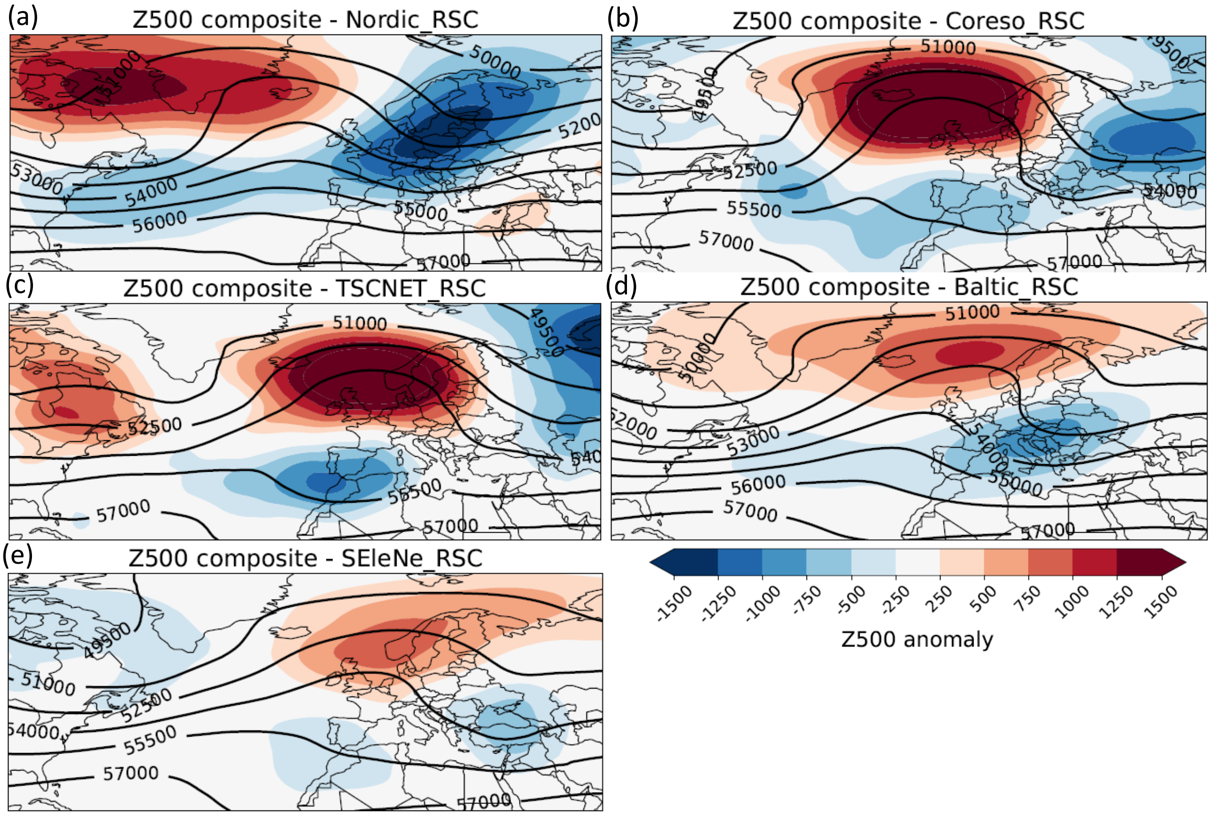
This highlights how interconnections with closest neighbouring countries would not be as helpful in these situations. It is important to note that the European Union has decided to prioritise the expansion of energy connectivity across Europe through “European electricity highways” for instance (European 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).

Simultaneous shortfall days are also associated with blocking type regimes. Figure 16 highlights that the most frequent regimes are ScBl, AtR and NAO- which are characterized 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.

Figure 16: Regime frequency during common days for the Nordic (a), Coreso (b), TSCNET (c), Baltic (d) and SEleNe (e) RSCs.



The prevalence of blocking-type regimes is further emphasised by looking at Z500 composites during the common shortfall days (Figure 17), showing a ridge formed over western Europe for all RSCs. The exact position and extent of this ridge changes the area that is likely to experience colder conditions or lower winds and therefore dictates the countries that could experience shortfall.


(a) Z500 composite - Nordic_RSC

(b) Z500 composite - Coreso_RSC

(c) Z500 composite - TSCNET_RSC

(d) Z500 composite - Baltic_RSC

(e) Z500 composite - SEleNe_RSC

Figure 17: 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.

iii. A plausible worst case scenario: the example of winter 1962-1963

The European winter of 1962-63 is known as its coldest winter of the 20th century (Hirschi & 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, 1970). This winter was synoptically characterised by a strong and persistent NAO- (Hirschi & Sinha, 2007; Greatbatch et al., 2015). While such severe winters are becoming less likely due to climate change, similarly cold or even colder winters are still possible (Sippel et al., 2024). Considering this, studying this winter provides valuable insight on what could be a worst case scenario for the energy sector. 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 18).

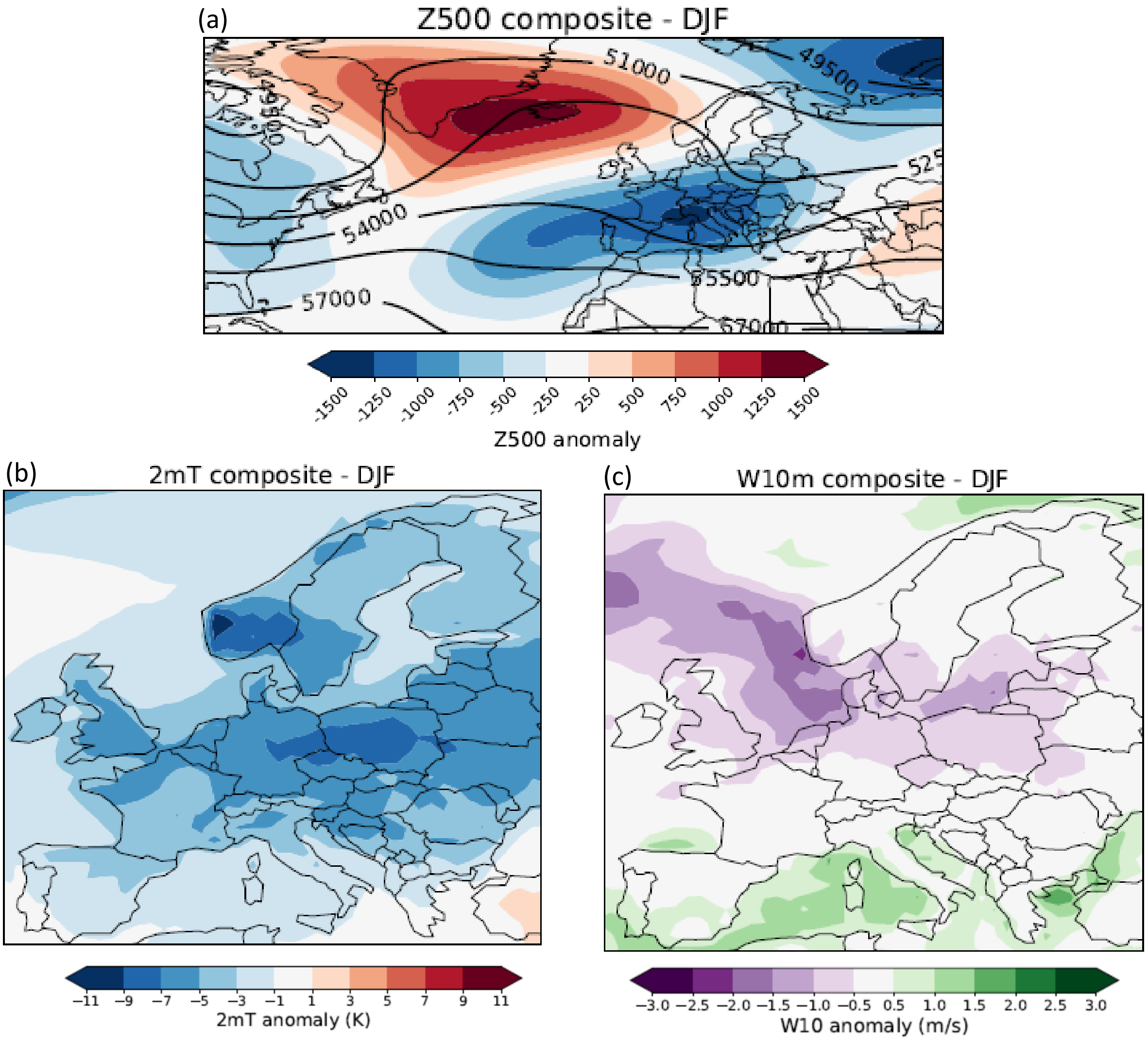


Figure 18: Composites for December, January and February from 1962 to 1963. Z500 absolute values in contouring and anomaly in colouring (a); 2mT anomaly in colouring (b); W10m anomaly in colouring (c).

The 2mT composite shows the expected strong negative temperature anomaly across all of Europe (Figure 18). The atmospheric circulation is characterised by a ridge over western Europe (Figure 18a), similar to that shown in Figure 17. Associated with the ridge, a negative wind anomaly covers the North Sea and parts of northern Europe.

The weather regime frequency during winter (DJF) shows the predominance of the NAO- regime (Figure 19), consistent with prior studies (Hirschi & Sinha, 2007; Greatbatch et al., 2015) and the ridge visible in the Z500 composite.

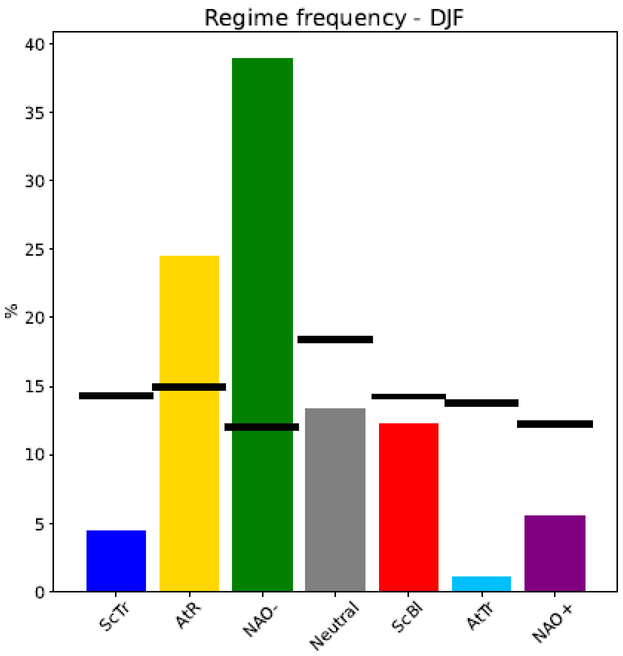


Figure 19: Regime frequency during 1962-1963 DJF period. Black lines show the climatological frequency of regimes.

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

The energy demand and shortfall in Figure 20 are normalised based on the DJF climatology 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 (in this limited dataset) experiencing 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 close to 10 standard deviations above the norm.

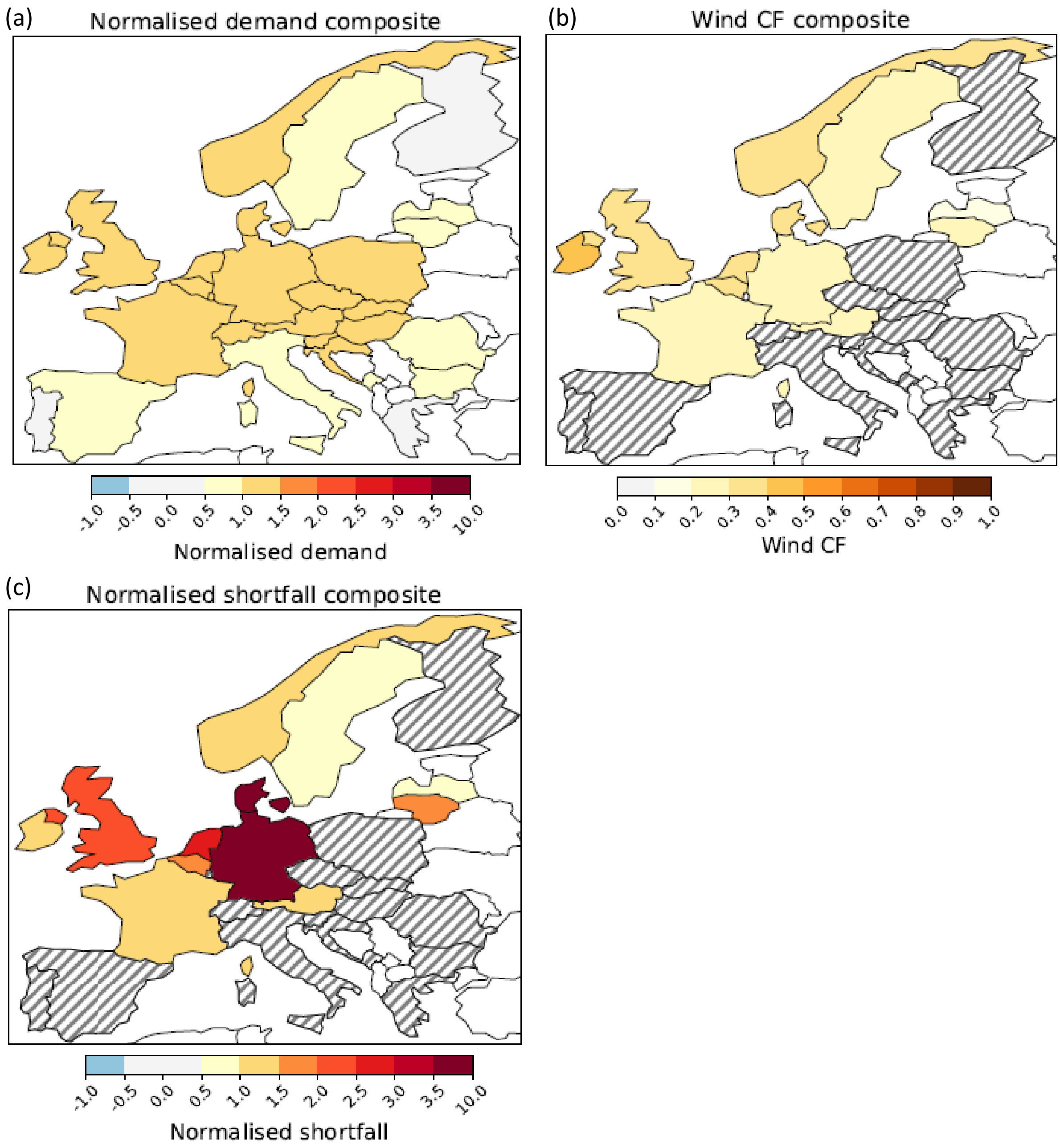


Figure 20: DJF energy composite conditions. Energy demand (a); Wind CF (b); Energy shortfall (c). Stripes in (b) and (c) show countries for which wind CF and shortfall data is not available.

The discrepancy can be partly explained by Germany and Denmark having colder temperatures already in December and being affected by the low wind conditions, as they are both high producers of renewable wind energy. Additionally, both countries can in certain circumstances have more renewable generation than demand, leading to negative shortfall. This results to a lower shortfall standard deviation.

To further understand the amplitude of the impact on the energy sector, Figure 21 shows the frequency ratio of both demand and shortfall days. This takes the frequency of demand or shortfall days during DJF and divides it by the average frequency during DJF of both kinds of energy days. This shows that for all countries for which data is available, the frequency of energy demand and shortfall days was above the norm. The frequency of demand days is at least twice as frequent as normal for most countries and up to 5 times as frequent for the United Kingdom and Netherlands. Shortfall days were at least twice as frequent for most countries and 3 times as frequent for Norway.

For both Germany and Denmark, the shortfall frequency ratio is not as high as the normalised shortfall composite could have suggested. This could be due to the lower shortfall standard deviation, as explained above.

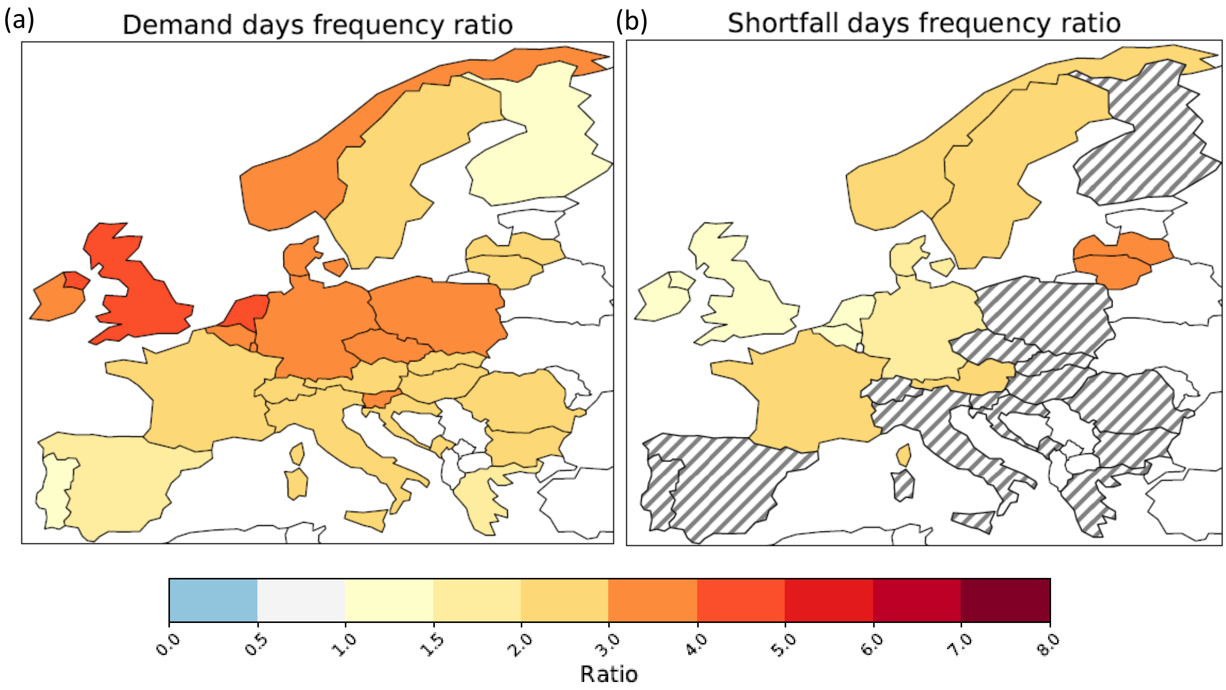


Figure 21: Frequency ratio of demand and shortfall days during DJF of 1962-1963. Stripes in (b) show countries for which shortfall data is not available.

This case study highlights how an extremely cold and persistent winter could affect the energy network in Europe. All countries would experience large demand and shortfall, leading to an increase in extreme energy situations over a long period of time. These situations 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.

4. 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 events, are crucial.

Several studies have investigated the influence of weather on energy shortfall using weather regimes (Mockert et al., 2022; van der Wiel et al., 2019b; Bloomfield et al., 2020a). In this paper, the relationship between shortfall days – days when the energy shortfall is above the 90th percentile – 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 – 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 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 one country in particular or Europe in general we provide a general look over Europe but also highlight differences between countries and their cause. Additionally, we provide a perspective on potential worst case scenarios over Europe.

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 both demand and shortfall days, presumably due to an increase in winter time temperatures. The relative dependence between shortfall days and demand or wind drought days varies between countries. Those with high installed wind capacity or southern countries have shortfall days that coincide more with wind days while countries with low installed wind capacity or northern countries have shortfall days that coincide more with demand days. 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., 2016).

Investigating the characteristics of energy events (consecutive energy days) depending on their duration showed that longer shortfall events also had higher shortfall. Thus these events are particularly critical to the energy network.

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. These results are supported by previous studies (Bloomfield et al., 2020a; Grams et al., 2017; van der Wiel et al., 2019b). 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. 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.

Finally, a case study was performed looking at the coldest winter of the 20th century in Europe. The aim is to determine what the impact of a worst-case scenario could be on the current energy network, since this winter is characterised with very persistent blocking regimes. We show that all European countries would experience higher than normal demand and shortfall with an increased frequency of both demand and shortfall days. Similar winters are unlikely but not impossible (Sippel et al., 2024), therefore an energy network more reliant on renewable energy sources needs to be prepared to weather these possible situations.

It is important to note that, throughout this study, modelled energy data is used with fluctuations being only due to weather conditions. This allows to get 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. However, comparing these results by using real world data would enable to quantify the relative influence of weather conditions compared with other components (e.g. network constraints, infrastructure, behaviour). In addition, it would be interesting to examine changes to the energy network following 2030 targets and their impact on the conclusions of this study. Also, this study focuses 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.

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Data Availability Statement

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/).

Conflict of Interest Disclosure

The authors declare that there are no conflicts of interest.

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