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Citation (APA)
Ho-Tran, L., & Fiedler, S. (2024). More summertime low-power production extremes in Germany with a larger solar power share. *Solar Energy*, *283*, Article 112979. https://doi.org/10.1016/j.solener.2024.112979

Solar Energy 283 (2024) 112979

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

More summertime low-power production extremes in Germany with a larger solar power share

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ARTICLE INFO

Dataset link: https://www.wdc-climate.de/ui/entryacronym=DKRZ_LTA_1198_ds00003

Keywords:
Extremes power production
Stationary weather pattern
Seasonality

ABSTRACT

The share of renewable energy in Germany is increasing to meet the climate-neutral targets in 2050. Weather-driven anomalous in renewable power production thus can pose greater challenges in balancing electricity supply and demand. This study investigates the seasonal differences in extreme events in photovoltaic (PV) plus wind power production in Germany for installed capacities for the present and 2050. The results indicate an increase in such extreme events in the summer half-year, mostly pronounced in May. Extremely low production with a duration of 14 days in winter is associated with atmospheric blocking, with very low wind power production anomalies of up to −37%. Summertime extremely low production is associated with stationary cyclonic weather patterns, with similar reductions in both energy sources of up to −19%. Case studies illustrate the dependency of the benefits of cross-border electricity transmission lines on the prevailing wind direction. North–South transmission lines are beneficial when an anticyclone moved from the Northwest to Germany, whereas West-East transmission lines are beneficial when a cyclone moved from the Southwest to Germany. The results imply an increased risk of extremely low power production during future summers in Germany and suggest monitoring sequences of different weather patterns for the energy sector.

1. Introduction

European countries are rapidly increasing the share of power production from renewable sources to reach the 2050 climate-neutral targets [1]. As part of this goal, the German government has set its target to increase the share of renewable sources in electricity generation to 80% and in gross energy consumption (including electricity, heating, cooling, and transport) to 60% by 2050 [2,3], compared to 49.6% and 20.4% in 2022 [4]. Wind and solar power are the two fastest-growing renewable sources in Germany. In 2022, wind and solar power (mainly photovoltaic) contributed 26% and 12% to electricity production in Germany [5]. The total installed capacities of onshore wind power and solar power in Germany have almost doubled over 10 years with 58 GW and 67 GW in 2022, compared to 31 GW and 33 GW in 2012. Particularly, German offshore wind power capacities have strongly increased from 0.3 GW in 2012 to 8 GWM in 2022 [6].

The high shares of renewable power sources make the electricity system susceptible to adverse weather conditions. One such challenge arises when both photovoltaic (PV) and wind power produce less than the expected amount for a prolonged period of up to 14 days [7]. Such low production events can be challenging with the currently available storage capacities for electricity in Germany, e.g., with 5.6 GW for battery [8] and 6.7 GW for pump storages [9]. Prolonged low production events can be especially problematic when they co-occur with an increased demand, e.g., for heating during cold spells [10].

Previous studies have primarily focused on anomalously low power production events occurring in winter [7,11,12], mostly caused by a reduction in wind power production [13]. However, extreme events in the energy system can also occur in summer. Summertime irradiance is larger than in winter making weather-driven extremes in power production more sensitive to potential reduction in PV power production. This dependency can increase in the future because the projected ratio of PV to wind power capacity for Europe is larger than today, e.g., 2:1 in 2050 [14] compared to 0.7:1 in 2019 [15]. Moreover, European PV power anomalies show a more homogeneous spatial distribution across seasonal to multidecadal weather variability in comparison to wind power in various installed capacity scenarios [16]. In consequence, an event of low PV power production can affect relatively large regions resulting in little opportunity for cross-border electricity transmission

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https://doi.org/10.1016/j.solener.2024.112979
Received 24 April 2024; Received in revised form 28 August 2024; Accepted 29 September 2024

of neighboring countries [13]. In addition, climate change leads to more frequent, intense, and prolonged heatwaves [17,18], which may increase the future electricity demand for cooling, akin to the demand for heating during cold spells in winter.

A study by [13] has identified synoptic weather conditions associated with low PV plus wind power production, hereafter referred to as total production in Europe, using the weather pattern classification from [19]. Specifically, using the European installed capacity projected for 2050, the pattern South-Shifted Westerly is associated with the lowest 1-day total production, while Anticyclonic South-Easterly is associated with the lowest 10-day total production event. The number of such weather patterns lasting for more than 10 days is limited with 19 events during the period 1995–2017. However, an energy system assessment points to the importance of sequences of several different weather patterns for anomalously low power production in Germany [10]. To what extent events composed of several weather patterns are more extreme in comparison to prolonged events with the same prevailing weather pattern has not been systematically studied in light of future capacities. The present study aims at helping to fill this knowledge gap.

We examine prolonged extremes in total power production in Germany with a focus on their seasonal differences. By performing PV and wind power simulations and pairing the results with a synoptic weather classification, this study provides evidence that there might be more prolonged low-production events in summer for the 2050 installation. Our study contributes to filling the gap in knowledge of how summertime low-production events differ from wintertime events, in terms of how PV and wind power production vary and what weather patterns drive extremes in production. Such knowledge is important for electricity system operators to issue warnings when the weather conditions associated with extreme events are forecasted. Moreover, the knowledge helps to mitigate potential impacts, e.g., by installing storage and suitable transmission lines for electricity to balance regional differences in production during extremes.

Detailed descriptions of the data and methods used in the analyses are provided in Section 2. The results first show the seasonal differences of events with anomalous PV and wind power production in Germany (Section 3.1). Section 3.2 compares the cyclonic and anticyclonic characteristics of weather patterns that are associated with extreme events occurring in winter and summer. To further examine prolonged low production events, ten low production events of a duration of 14 days were selected and examined (Section 3.3), and two case studies are analyzed in detail in Section 3.4. Finally, the discussion and conclusion of the results are presented in Sections 4 and 5.

2. Methods

2.1. Data

Our analysis of extremes in total production (PV plus wind power production) is based on simulations with the Renewable Energy Model (REM), which has been described and used in an earlier article [13]. REM was developed to simulate PV and wind power production using meteorological and power installation data for Europe. In REM, the meteorological data are from the reanalysis dataset COSMO-REA6 [20] with a high horizontal resolution of 6 km. Validation tests of REM output against Renewables Ninja [21,22] and CDS data [23] show good temporal correlations of 0.88–0.98 for PV power and 0.75–0.97 for wind power onshore, and potential capacity factors in agreement for PV power (in the range of 12% to 14%) and wind power onshore (around the value of 24%) for four selected countries in 1995—2017 [13]. The potential capacity factors (potentials) of PV and wind power production were calculated based on COSMO-REA6 data using a power-rating method with effective irradiance, including direct and diffused radiation, on crystalline silicon PV modules [24] with the azimuth angles facing south and the optimal tilt angles of 21° to 50° for European countries [25] multiplied by 0.7 as investors usually opt for lower tilt angles to reduce the shadow effects [26]. The potentials of wind power were calculated using a cubic power curve with the cut-in, rated, and cut-out wind speeds of 3.5, 13, and 25 m/s. Wind speeds were taken from COSMO-REA6 data at the two model levels 36 and 37 with average heights of 116 m and 178 m over the European domain.

The potentials were then multiplied by the installed capacities from CLIMIX to get power production of wind and PV power. The data on power installation in REM include the spatial distribution and installed capacity of PV and wind power in Europe at a horizontal resolution of 11 km from the model CLIMIX (CLImate and energy MIX) by [14]. CLIMIX allocates the installed capacities of PV and wind power reported for present-day and planned for 2050 from each country into a grid of 0.11° based on criteria such as resource availability, population, and restricted areas. The output of REM is the hourly production of PV and wind power in every eight grid box, i.e., at a horizontal resolution of 48 km but with an effective resolution of 6 km for the meteorological processes. Our study is based on one scenario of installed capacity projected for 2050 from the CLIMIX model [14]. The results can vary depending on the ratio of PV and wind power and the future spatial distribution of their installation. CLIMIX is shown to be conservative for wind power, e.g., 440 GW for Europe in 2050 compared to another projection of 620 GW [27]. A higher ratio of PV to wind installed capacity, e.g. 5:1, would decrease the total power anomalies in individual weather patterns but not the overall anomalies across all patterns [13].

To assess the dependency of power production anomalies on the installed capacity, we performed and compared the following two experiments with the same meteorological data for 1995–2017 and different installed capacities.

- scenario-2050: REM simulation for a future installation using the scenario for 2050 obtained from the CLIMIX model [14]
- scale-2019: REM simulation for a present-day installation derived by scaling the scenario-2050 installation to match the European installed capacity in 2019 [15]

The scaling for obtaining the scale-2019 installation was necessary due to the lack of a suitable gridded data set covering all of Europe. We used country-aggregated installations of the year 2019 [15] for the scaling. The corresponding REM experiment scale-2019 yields a ratio of the annual PV to wind power production and total installed capacities for Germany that closely aligns with data reported for 2015 [12]. Moreover, the experiment scale-2019 reproduces the weather pattern associated with the lowest total power production for Germany [12,13]. See [13] for more details on the methods and underlying data. Note that the scaling method retains the same spatial distribution of installed capacities between the two examined scenarios. The future spatial distribution of PV and wind power installation can differ from scenario-2050 depending on the countries' plans and implementation. However, we perceive scenario-2050 as a plausible future scenario since CLIMIX has taken into account the resource availability and countries' plans for future investments. The scenario 2050 from the CLIMIX model has been used in several publications before to assess renewable power production variability [7,28–31]. Validation of CLIMIX model shows reasonable agreement to past power production records for most countries [14], albeit with larger values due to the overestimation of the model simulation [32] and assumptions that all planned power plants operate and function well at the same time [14]. Maps of PV and wind power installed capacity in scenario-2050 is shown in [13].

To examine the impact of synoptic weather conditions on PV and wind power production, we pair each day in the timeseries from REM output with a weather pattern from the classification comprising 29 patterns [19]. In this classification, the weather patterns are distinguished based on the position of dominant pressure systems, their cyclonic or anticyclonic characteristics, and the prevailing wind direction over Central Europe [19]. We further assessed the 2 m temperature, mean-sea-level pressure, and downward direct and diffuse shortwave radiation from COSMO-REA6 to characterize the meteorological developments during extreme events in total power production.

2.2. Analysis strategy

In this study, we define extreme events based on the time series of total power production in Germany. These time series are derived by taking the mean values of PV and wind power production across all grid cells with available data within Germany from the REM output. The grid cells were selected using a pre-defined shapefile [33]. We selected PV power and onshore wind power production in Germany for the analyses of our experiments. The installed capacities for Germany are 88.5 (12.2) GW for PV power and 33.1 (12.6) GW for onshore wind power in scenario-2050 (scale-2019), resulting in a ratio of PV to wind power installation of about 2.5:1 (1:1). The analysis includes only wind power onshore in Germany inside the shapefile (Supplementary Fig. S1). Wind power offshore could reach 45–70 GW in Germany in 2050, decreasing the ratio of PV to wind power installation to between 1.2:1 and 2.3:1 [34], still within the range of ratio between scale-2019 and scenario-2050 installations. The lower ratio means the influence of PV power on total production anomalies would reduce and the influence of wind power would be further enhanced, the overall effect on the total production anomalies would be similar to scenario-2050 but with lower magnitudes.

Wind power has a strong influence on total production in scale-2019 and is higher in winter than in summer [13], while PV power produces a larger amount during summer than in winter. To account for the seasonality of production, we calculate normalized power production anomalies time series to represent deviations from the climatological mean power production for a given time of year. We first calculated hourly anomalies of power production against the climatological mean with the same hour, day and month of every year for the entire period. Then we summed the hourly data to obtain daily time series to be comparable with weather pattern data and analyze 1-, 7-, and 14-day events.

We statistically analyze prolonged anomalously high and low production events associated with weather patterns. Our selection of the 50 most extreme total production events for each category, i.e., for the lowest and highest total production, and each duration of 1, 7, and 14 days. We defined prolonged low production events with a duration of 14 days because German energy deficits increase monotonically up to 14 days [35]. The time windows of 1 and 7 days were selected to represent the short and medium length of events, as used in a previous study for Europe [7]. Tests of other time windows in the context of power production anomalies associated with weather patterns show similar results amongst events with duration differences of up to two days [13]. For instance, to define the 50 lowest total production events with a 14-day duration, we used the time series of daily anomalies for the period 1995–2017 to first calculate the moving average over 14-day time windows. Then, we select the 50 dates with the lowest moving average. These 50 dates are assigned as the central dates of the 14-day events with extremely low production. When two events have their central dates closer than 14 days to each other, one of the events was removed before further analyses to avoid counting the same event more than once. During 7- and 14-day events the sequences of weather patterns can contain a mix of cyclonic and anticyclonic patterns depending on how the weather conditions develop.

Monthly statistics are calculated based on the central dates of the events for each event duration, namely the first, fourth, and eighth days of the duration 1-, 7-, and 14-day, respectively. The statistics for the weather patterns were computed per event, i.e., considering all dates during the duration of the events. For each category of highest or lowest power production, we selected the 50 most extreme events per duration, with 50 days for 1-day events, 350 days for 7-day events, and 700 days for 14-day events, resulting in 2200 days in total. To account for a higher frequency of occurrence of some weather patterns, the frequencies of patterns for extreme production events were normalized by the climatological mean of the frequency of occurrence of the weather patterns (1995–2017) separately for winter and summer. For the seasonal division, we adopted the same two half-year seasons to be consistent with the weather pattern classification as in [19], namely summer from April 16th to October 15th and winter from October 16th to April 15th.

We aim to better understand the seasonal differences in the power production anomalies in Germany from a meteorological perspective. To that end, we first investigate the anomalies in total power production associated with different weather patterns separated into cyclonic and anticyclonic characteristics. Out of 29 weather patterns, 16 are cyclonic patterns denoted by the letter *z* for *zyklonal* in German or *T* for *Trough* or *Tief* (low) in German, and 13 are anticyclonic patterns denoted by the letter *a* or *H* for high pressure [19]. Fig. 3 shows the frequency of occurrence of cyclonic and anticyclonic patterns associated with the 50 most extreme production events for each duration of 1, 7, and 14 days. To further examine the seasonal differences between prolonged low production events in winter and summer, we also select the two most extreme 14-day events to perform two case studies, based on the weather in December 2007 and May 2016 to analyze in detail the co-development of power anomalies and weather conditions.

3. Results

3.1. Seasonal differences

The experiment scenario-2050 shows four times more summer events with extremely low total power production over Germany compared to scale-2019. Namely, out of all 150 lowest production events with 1-, 7-, and 14-day durations, 22% occurred in summer compared to 5% in scale-2019 (Fig. 1a,c). The largest difference is seen for the 14-day lowest production events in summer, with 25% (5%) of the 50 lowest production events in scenario-2050 (scale-2019). None of the 50 lowest production events with 1-day duration occurs in summer for scale-2019, but 14% are seen in summer in scenario-2050. For 7-day lowest production events, the occurrence more than doubles with the future installed capacities with 6% in scale-2019 to 15% in scenario-2050. Nevertheless, the most extreme low production events occur more frequently in winter (Fig. 1), consistent with previous studies with various durations of events for Germany [12] and Europe [7]. Most extreme production anomalies are seen around December and January for both installations (Fig. 1c), which is two months later than in [7]. The difference might be due to their assessment of Western Europe, whereas we focus here on Germany.

May has of all months the largest increase of extremely low power production events in scenario-2050 for all durations with 2–3.3% of the 150 most extreme events falling into this month, in comparison to no extreme events in scale-2019 (Fig. 1a,c). This increase in the occurrence of extremes in May is due to its higher frequencies of weather patterns with anomalously low irradiance and thus low PV power production, e.g., Cyclonic North-Easterly (NEz), Icelandic High, Trough Central Europe (HNz), and Low Cut-Off over Central Europe (TM) (Fig. 2). The full list of names of the weather patterns is given in Supplementary Table S1. One example is the 14-day event on 8–21 May 1996, of which eight days had the pattern NEz. A strong extratropical cyclone with a center over the south of Italy and a core pressure of 998 hPa (Supplementary Fig. S2) led to anomalously high cloud cover over Germany reducing irradiance at the surface. As a result, an extremely low PV power production was simulated with up to −36% on 11 May which was very low compared to the composite mean for the NEz pattern of −2% for Germany [13]. The extremely low PV power production has a higher influence on total production in scenario-2050

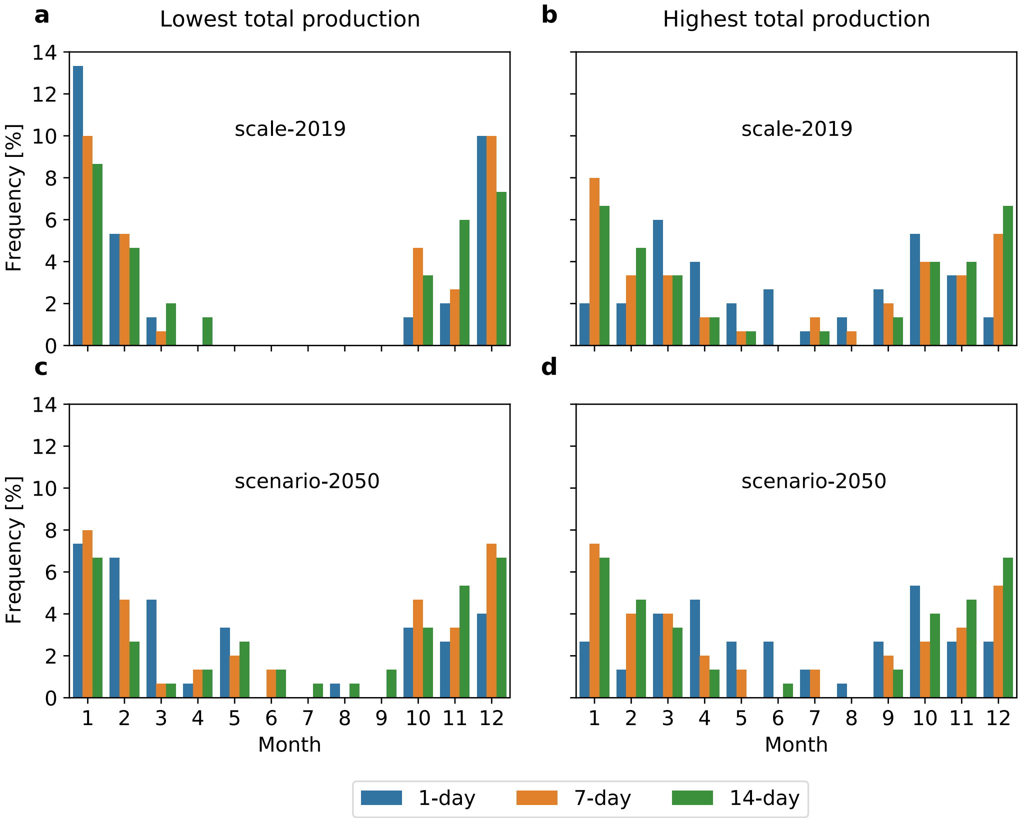


Fig. 1. Monthly distribution of the most extreme power production events. Shown are the 50 most extreme events color-coded for each duration of 1, 7, and 14 days for the lowest total power production (left) and the highest total power production (right) aggregated for Germany, simulated with scale-2019 (top) and scenario-2050 (bottom) installed capacities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

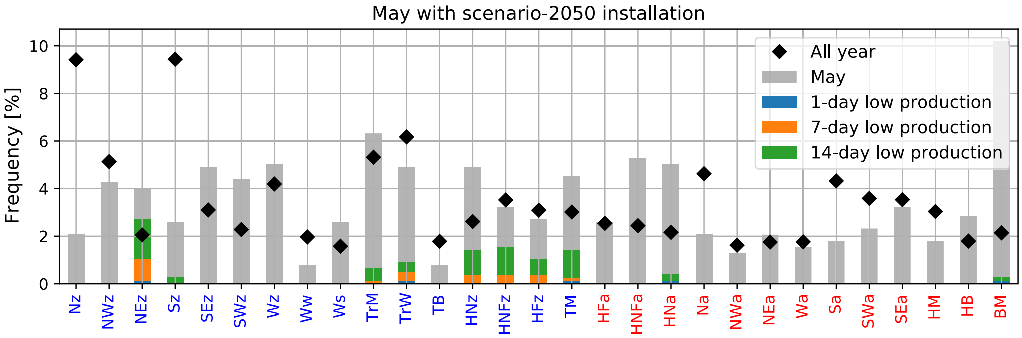


Fig. 2. Frequency of co-occurring weather patterns and lowest power production events in May. Shown are the relative frequency of weather patterns occurring in May (gray bars) and the whole year (black diamonds) over the period 1995–2017. Included in the gray bars are the percentages of days with extremely low total production events in May co-occurring with the weather patterns (5,3, and 4 events with the duration 1, 7, and 14 days, respectively) simulated in scenario-2050. Weather patterns written in blue have cyclonic characteristics, while weather patterns written in red have anticyclonic characteristics. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

due to a higher share of PV power installations compared to scale-2019. Consequently, this event had the sixth lowest total production in scenario-2050 in summer but was not in the top 50 lowest production events in scale-2019.

Most of the highest production events also occur in winter in the experiment scale-2019, with 82% of 150 events with high extremes compared to 95% of the low extremes (Fig. 1a,b). For the high extremes in power production, changes in the seasonal differences are moderate between the two installations, with percentages of events occurring in summer increasing up to 3% for each duration (Supplementary Table S2). For both installations, the 7- and 14-day high extremes occur most frequently in January due to winter cyclones associated with strong winds. For 1-day high extremes, the simulations show later maxima in the occurrence of extremes, with a shift of the maximum from March to April when we go from scale-2019 to scenario-2050 (Fig. 1b,d). Again, this is due to the higher share of PV in scenario-2050 such that the influence of the stronger irradiance towards spring has a larger effect on the total power production.

3.2. Cyclonic and anticyclonic characteristics

Most events with low extremes are associated with anticyclonic weather patterns for all durations in scale-2019 explaining 60%–66% of all events (Fig. 3a–c). In scenario-2050, anticyclonic patterns also explain 52%–54% of events with a duration of 7 and 14 days, but less than half (42%) of the 1-day extreme events (Fig. 3a). Consequently, cyclonic patterns show an increase in association with 1-day lowest

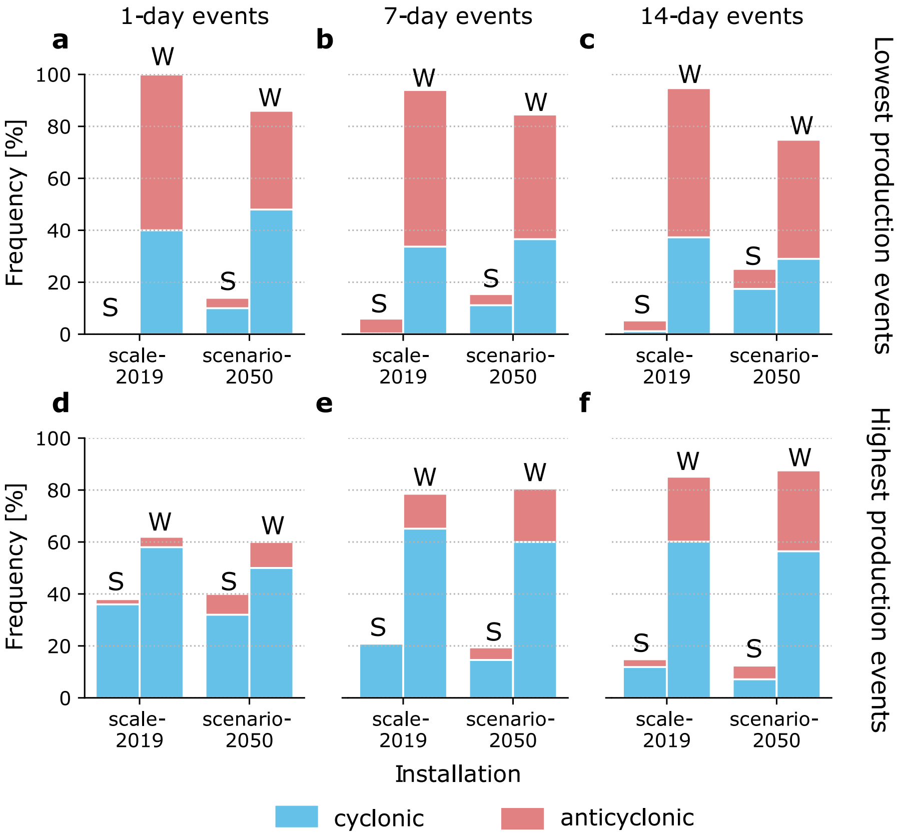


Fig. 3. Frequency of co-occurrence of power production extremes with cyclonic and anticylonic weather patterns in winter and summer. Shown are the number of cyclonic (blue) and anticyclonic (red) weather patterns associated with the 50 lowest (a–c) and highest (d–f) total power production events in summer (S) and winter (W) half-years for each duration 1, 7, and 14 days, calculated in percentage of day for scale-2019 and scenario-2050 installations with weather data of 1995–2017 in Germany. Quantitative statistics are listed in Supplementary Table S2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

production events from scale-2019 to scenario-2050, both in winter (from 40% to 48%) and summer (from 0 to 10%). The higher frequency of cyclonic patterns on the lowest production events in scenario-2050 is due to their low irradiance and the higher influence of low PV power anomalies on total production, particularly in summer (Fig. 3a). Similar increases in the frequencies of cyclonic patterns are also seen in summer for 7-day events from 0 to 11% and for 14-day from 1% to 17% (Fig. 3b,c, Supplementary Table S2). However, weather patterns leading to the largest number of extremely low production events show cyclonic characteristics, specifically the pattern Cyclonic South-Easterly (SEz) for all three durations 1,7, and 14 days (Supplementary Table S1 and Fig. S3). The weather pattern SEz is known as Dark doldrum pattern for Europe, associated with simultaneously low production in PV and wind power [13].

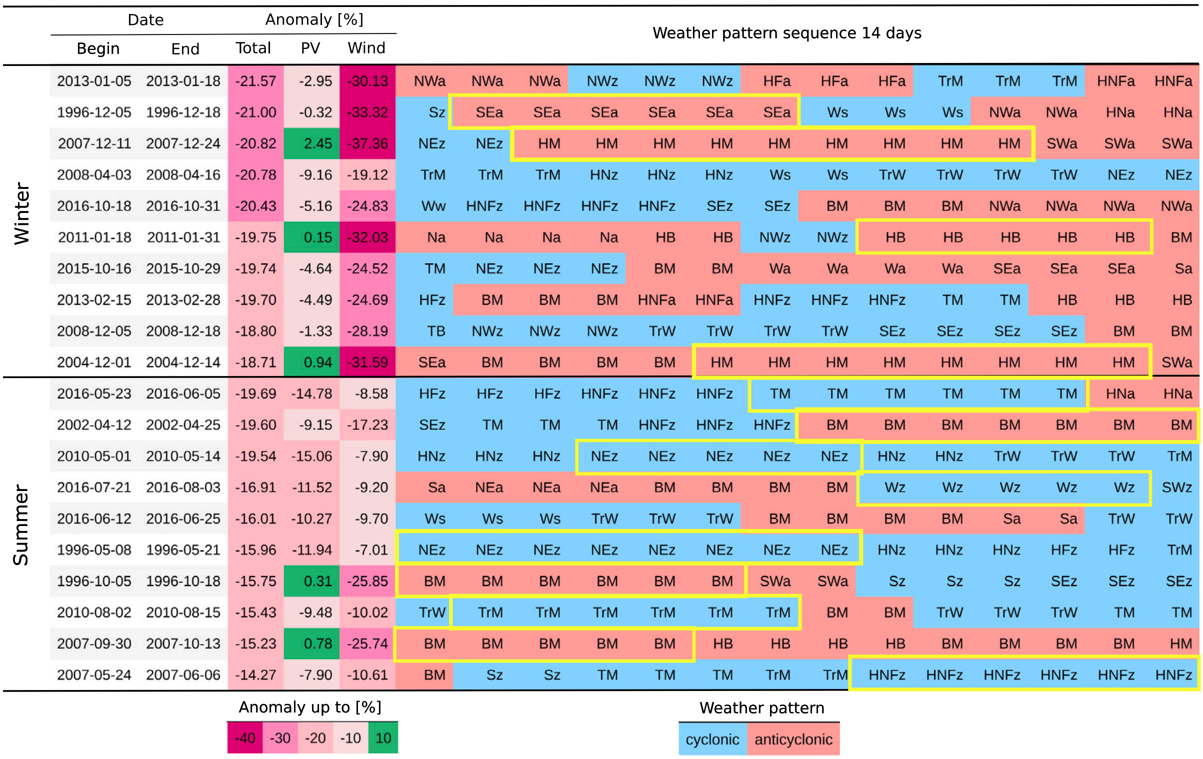
In contrast to the prevalence of anticyclonic patterns in the 50 lowest power production events, the highest power production events are predominantly associated with cyclonic patterns independent of the event durations and season, explaining namely 72%–94% of the extreme events in scale-2019 and 63%–82% in scenario-2050 (Fig. 3d–f, Supplementary Table S2). In particular, the events with the highest 1-day production coincide mostly with cyclonic weather patterns, namely 94% (82%) of the cases in scale-2019 (scenario-2050), and have relatively less pronounced seasonal differences than the longer events (Fig. 3d). High production events are characterized by westerly winds over Central Europe and the North Sea, e.g., Wz, SWz, and NWz (Supplementary Fig. S4), consistent with findings for Europe [13]. Noticeably, the pattern Scandinavia-Iceland (HNFa), which is not related to high production events in scale-2019, sees a substantial increase in the number of extreme events in scenario-2050 (Supplementary Fig. S4), primarily in winter. The pattern shows a ridge over Central Europe that leads to anomalously high irradiance and therefore amplifies the impact of the higher future PV power share in Germany.

3.3. Prolonged low production events

We compare the meteorological conditions during the 14-day lowest production events between winter and summer using ten events for each half-year season (Fig. 4). Overall, 14-day lowest production events in winter are associated with anticyclonic patterns (59% of days), while those in summer are more likely associated with cyclonic patterns (66% of days). There are no particularly repeating weather pattern sequences during these lowest production events, but rather the low production comes from combinations of several weather patterns with low PV and/or wind power production.

In certain years, such as 1996, 2007, and 2016, extremely low power production events occurred in both winter and summer. Noticeably, three out of the five lowest total production 14-day events occurred for the weather of summer 2016. This might be linked to the anomalous activity of the Rossby waves in 2016 [36]. Under certain conditions, Rossby waves favor blocking which is linked to the development of heat waves and cold spells [37], e.g., the unusual heatwaves across Western Europe in 2016 [36]. This blocking in summer 2016 also resulted in prolonged periods of anomalously low wind speeds which caused the reduction in wind power production in Germany in May, June, and July 2016 (Fig. 4).

Stationary weather patterns play a substantial role in prolonged low-production events, e.g., a blocking high-pressure system like during 2016. Here we define stationary weather patterns when the same pattern occurs for at least five consecutive days, following the criteria for an atmospheric blocking [38]. Specifically, 13 of the 20 lowest



	Date		Anomaly [%]			Weather pattern sequence 14 days													
	Begin	End	Total	PV	Wind														
Winter	2013-01-05	2013-01-18	-21.57	-2.95	-30.13	NWa	NWa	NWa	NWz	NWz	NWz	HFa	HFa	HFa	TrM	TrM	TrM	HNFa	HNFa
	1996-12-05	1996-12-18	-21.00	-0.32	-33.32	Sz	SEa	SEa	SEa	SEa	SEa	SEa	Ws	Ws	Ws	NWa	NWa	HNa	HNa
	2007-12-11	2007-12-24	-20.82	2.45	-37.36	NEz	NEz	HM	HM	HM	HM	HM	HM	HM	HM	HM	SWa	SWa	SWa
	2008-04-03	2008-04-16	-20.78	-9.16	-19.12	TrM	TrM	TrM	HNz	HNz	HNz	Ws	Ws	TrW	TrW	TrW	TrW	NEz	NEz
	2016-10-18	2016-10-31	-20.43	-5.16	-24.83	Ww	HNFz	HNFz	HNFz	HNFz	SEz	SEz	BM	BM	BM	NWa	NWa	NWa	NWa
	2011-01-18	2011-01-31	-19.75	0.15	-32.03	Na	Na	Na	Na	HB	HB	NWz	NWz	HB	HB	HB	HB	HB	BM
	2015-10-16	2015-10-29	-19.74	-4.64	-24.52	TM	NEz	NEz	NEz	BM	BM	Wa	Wa	Wa	Wa	SEa	SEa	SEa	Sa
	2013-02-15	2013-02-28	-19.70	-4.49	-24.69	HFz	BM	BM	BM	HNFa	HNFa	HNFz	HNFz	HNFz	TM	TM	HB	HB	HB
	2008-12-05	2008-12-18	-18.80	-1.33	-28.19	TB	NWz	NWz	NWz	TrW	TrW	TrW	TrW	SEz	SEz	SEz	SEz	BM	BM
	2004-12-01	2004-12-14	-18.71	0.94	-31.59	SEa	BM	BM	BM	BM	HM	HM	HM	HM	HM	HM	HM	HM	SWa
Summer	2016-05-23	2016-06-05	-19.69	-14.78	-8.58	HFz	HFz	HFz	HNFz	HNFz	HNFz	TM	TM	TM	TM	TM	TM	HNa	HNa
	2002-04-12	2002-04-25	-19.60	-9.15	-17.23	SEz	TM	TM	TM	HNFz	HNFz	HNFz	BM	BM	BM	BM	BM	BM	BM
	2010-05-01	2010-05-14	-19.54	-15.06	-7.90	HNz	HNz	HNz	NEz	NEz	NEz	NEz	NEz	HNz	HNz	TrW	TrW	TrW	TrM
	2016-07-21	2016-08-03	-16.91	-11.52	-9.20	Sa	NEa	NEa	NEa	BM	BM	BM	BM	Wz	Wz	Wz	Wz	Wz	SWz
	2016-06-12	2016-06-25	-16.01	-10.27	-9.70	Ws	Ws	Ws	TrW	TrW	TrW	BM	BM	BM	BM	Sa	Sa	TrW	TrW
	1996-05-08	1996-05-21	-15.96	-11.94	-7.01	NEz	NEz	NEz	NEz	NEz	NEz	NEz	NEz	HNz	HNz	HNz	HFz	HFz	TrM
	1996-10-05	1996-10-18	-15.75	0.31	-25.85	BM	BM	BM	BM	BM	BM	SWa	SWa	Sz	Sz	Sz	SEz	SEz	SEz
	2010-08-02	2010-08-15	-15.43	-9.48	-10.02	TrW	TrM	TrM	TrM	TrM	TrM	TrM	BM	BM	TrW	TrW	TrW	TM	TM
	2007-09-30	2007-10-13	-15.23	0.78	-25.74	BM	BM	BM	BM	BM	HB	HB	HB	HB	BM	BM	BM	BM	HM
	2007-05-24	2007-06-06	-14.27	-7.90	-10.61	BM	Sz	Sz	TM	TM	TM	TrM	TrM	HNFz	HNFz	HNFz	HNFz	HNFz	HNFz

Fig. 4. Weather patterns in 20 lowest 14-day power production events in Germany, including 10 events in winter and 10 events in summer. The beginning and ending dates (inclusive) and anomalies (moving average 14 days). Half-year winter is 16 Oct–15 Apr, and half-year summer is 16 Apr–15 Oct. Anomalies are as deviations from their climatological means (see Methods). The color denotes anomalies in intervals of 10%. Weather patterns colored in blue (red) have cyclonic (anticyclonic) characteristics. Sequences with stationary weather patterns that last at least five days are highlighted in bright yellow rectangles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

power production events of a duration of 14 days are characterized by a stationary weather pattern for five or more consecutive days, marked by yellow rectangles in Fig. 4. The characteristics of the stationary weather patterns depend on the season of the event. Nine of ten events in summer contain a stationary weather pattern, six among which are associated with cyclonic patterns, e.g., TM, NEz, Wz, TrM, HNFz (Fig. 4). These events are characterized by relatively low production in both PV and wind power, simultaneously contributing to the anomalously low total production, e.g., events in May 2016, May 1996, August 2010, and April 2002 with anomalies in PV and wind power production of up to −11.7% and −17.2%.

Four of ten lowest production events in winter (December 1996, December 2007, January 2011, December 2004) are associated with stationary anticyclonic weather patterns, e.g., SEa, HM, HB, identified as atmospheric blocking with a known link to weather extremes, e.g., cold spells, heat waves, and droughts [39]. These events involve stationary high-pressure systems, resulting in low wind speeds and cloud covers ranging from 60% to 72% over Germany, close to the climatological winter mean for 1995–2017 (65%). The PV power production was therefore close to the seasonal average (−0.3 to 2.5%). Anomalously low total production is explained by the low wind speeds which led to extremely low wind power production during these blocking events, with anomalies an order of magnitude lower than that of PV power (up to −37%) (Fig. 4). High pressure over Central Europe (HM) occurred as two blocking events in December 2007 and December 2004, consistent with the role of HM in low production for events with a duration 120 h (5 days) in Germany as reported in a previous study [12]. Additionally, Anticyclonic South-Easterly (SEa) was a stationary weather pattern in the December 1996 event, a pattern known for 10-day low production events for both present-day and future installations in Europe [13].

Some events occurring during the transitional times between the winter and summer half-year exhibited the characteristics of events in the other season. The transitional times are typically two weeks around the dates of seasonal division, i.e. 15 April and 15 October [19]. For example, one event in late winter (April 2008) shares similar characteristics with summer events with relatively low production in both PV and wind power (−9% and −19%, respectively), whereas two events in late summer (October 1996 and October 2007) share similar characteristics with winter events with very low wind power production (up to −26%) and slightly above average PV power production (up to 1%) (Fig. 4).

3.4. Case studies

Two case studies were selected for further analysis of how the meteorological development influenced the power production of PV and wind power over time in Germany: (1) The event in December 2007 represents the third lowest 14-day total production event in winter with a significant impact in the simulation of Germany's electricity system [10]; (2) the event in May 2016 was selected because of its representative meteorological conditions during summer events with the lowest anomaly of total production (19.7%, Fig. 4). Figs. 5 and 7 show the sequences of weather patterns, the development of the meteorological variables 2m-temperature, mean sea level pressure, 10m-wind speed, and surface irradiance, and the associated anomalies in the power production. We show the development for seven days before and seven days after the central date of the events, resulting in a total of 28 days. It allows us to assess the weather conditions ahead of the extreme events and the subsequent recovery of the production. To explore the possibility of importing electricity during shortages in Germany, we include time series of the corresponding power production anomalies in the neighboring countries France and Denmark, two of the countries trading energy with Germany most frequently [8]. Similar figures for the ten lowest production events for each season (as in Fig. 4) are shown in Supplementary Figs. S5 and S6.

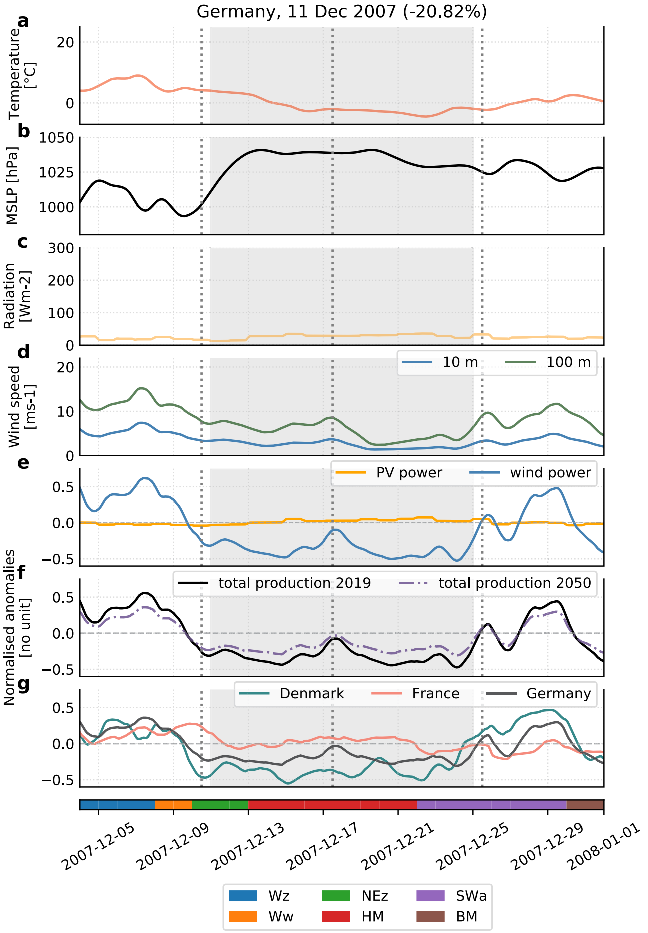


Fig. 5. Meteorological development during the 14-day low production event in Germany in the winter 11–24 December 2007. Shown are meteorological variables including 2-m temperature (a), mean sea level pressure (MSLP) (b), wind speed at 10 m and 100 m (c), and irradiance (downward short-wave direct and diffused radiation) (d), and normalized anomalies of energy variables including PV, wind power onshore (e), total production for *scale-2019* and *scenario-2050* installations (f), and total production of Germany and two neighboring countries Denmark and France (g). The figures are shown with moving averages of 24 h to smooth the diurnal variation. Vertical dotted lines mark three selected times to show the spatial variations of meteorological conditions and power production anomalies in Fig. 6. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4.1. *Winter event: December 2007*

On December 8, 2007, a low-pressure system formed in the North Atlantic, resulting in increased Westerly wind and cloud cover (72%) over Germany, leading to higher wind power (44%) and slightly lower PV power production (−3%, Fig. 5). The system moved southeastward with the center located over Germany, decreasing wind power production in Germany (−13%), initiating the 14-day low production event on December 10 (Fig. 6c). This system formed a cyclonic flow with Northeasterly wind (NEz) over the eastern coast of Great Britain, increasing wind power production in the southwestern tip of Germany, France, and the northern part of Spain (Fig. 6d). Additionally, from December 12 the Northeasterly wind directed cold air from the Arctic to Germany, increasing the energy demand for heating [10] (Fig. 5a). Simultaneously, a ridge formed in the south of Europe, with an axis extending from the west coast of Spain to Iceland (Fig. 6c). A stationary high-pressure system formed over Central Europe (HM) lasting from December 13 to 22. The high-pressure system was associated with slightly higher PV power production up to 10% on December 15 due to less cloudiness (cloud cover of 63%). However, the seasonally lower irradiance in winter did not compensate for the very low wind power production of up to −54% on December 14, resulting in an overall very low total production of up to −25% on December 14.

In the middle of the event, on December 17, 2017, a small cyclonic system formed in the Mediterranean. At its intersection with the existing high pressure over Central Europe, wind speeds increased in southwest Germany, while low wind power production persisted in the northeast of the country (Fig. 6g). A temporary increase in wind power in southern Germany alleviated the power shortage on the 17th but this recovery was short. Given that southern Germany currently has a lower number of batteries and pumped storage compared to the north [40], this brief recovery might not have been sufficient to replenish storage during the prolonged low production event. By December 18, the cyclonic system in the Mediterranean weakened and the influence of the high-pressure system dominated in Central Europe, reducing wind power production again on the 19th (Fig. 5).

The high-pressure system had a core pressure of more than 1025 hPa and had the core over Central and Southern Europe. It weakened on the 21st (Fig. 5) when a low-pressure system formed near Iceland. It resulted in strong Southwesterly winds over the North Sea (Fig. 6k), increasing wind power production in Germany on the 25th. This increased wind power production spread from the northwestern coast (Fig. 6l) to the rest of the country the following days, reaching the most positive anomalies of total production on the 29th (37%, Fig. 5) before decreasing again with the new weather condition (BM). The Southwesterly wind brings milder temperatures above zero degrees Celcius from the south of Europe to Germany. The higher temperatures would have also reduced the energy demand for heating, further alleviate the stress on the German electricity provision.

3.4.2. *Summer event: May 2016*

The meteorological development of the summer event in May 2016 was characterized by cyclonic weather patterns with a surface low-pressure system over Central Europe, including a stationary Cut-Off Low over Central Europe (TM) for six days from May 29 to June 3, along with Scandinavian High, Trough Central Europe (HFz) and High Scandinavian-Iceland, Trough Central Europe (HNFz) (Fig. 7).

On May 21, a low-pressure system north of Great Britain moved southeastward, weakened, and formed a trough over Germany on May 22. At the same time, a high-pressure system located in Eastern Europe (Fig. 8c). The pressure gradient between the two pressure systems increased the wind speeds, leading to higher wind power production in the north and west of Germany. The regional above-average production balanced the low wind power production in eastern Germany (Fig. 8d), resulting in a German wind power production close to the climatological mean on May 22 (Fig. 7e). Also along the pressure gradient between two pressure systems, increased cloud cover led to reduced surface irradiance and hence below-average PV power production in France on May 22 (Fig. 8a,b). In the following days, the area between two pressure systems moved eastward, affecting Germany, leading to a very low PV power production with daily anomalies of up to −48% on May 25. The positive anomaly of wind power production (20%) did not balance the very low PV power production, resulting in a very low total production anomaly of −73% on May 24. By May 26, the trough dissolved with a higher pressure area arriving from the west of Germany, and PV power returned closer to the climatological mean at −11% (Fig. 7).

In the middle of this 14-day low production event, the German total production temporarily increased on May 30. This was caused by a cut-off low-pressure system over Central Europe (TM) on May 29 (Fig. 8b). This low-pressure system remained stationary until June 4. Its strong pressure gradients led to high wind speeds and therefore high wind power production along the North Sea and the border of Germany near France, balancing the low wind power production in the southern parts of Germany (Fig. 8g,h) and leading to an above average wind power production in Germany on May 30 (Fig. 7). Cloudy

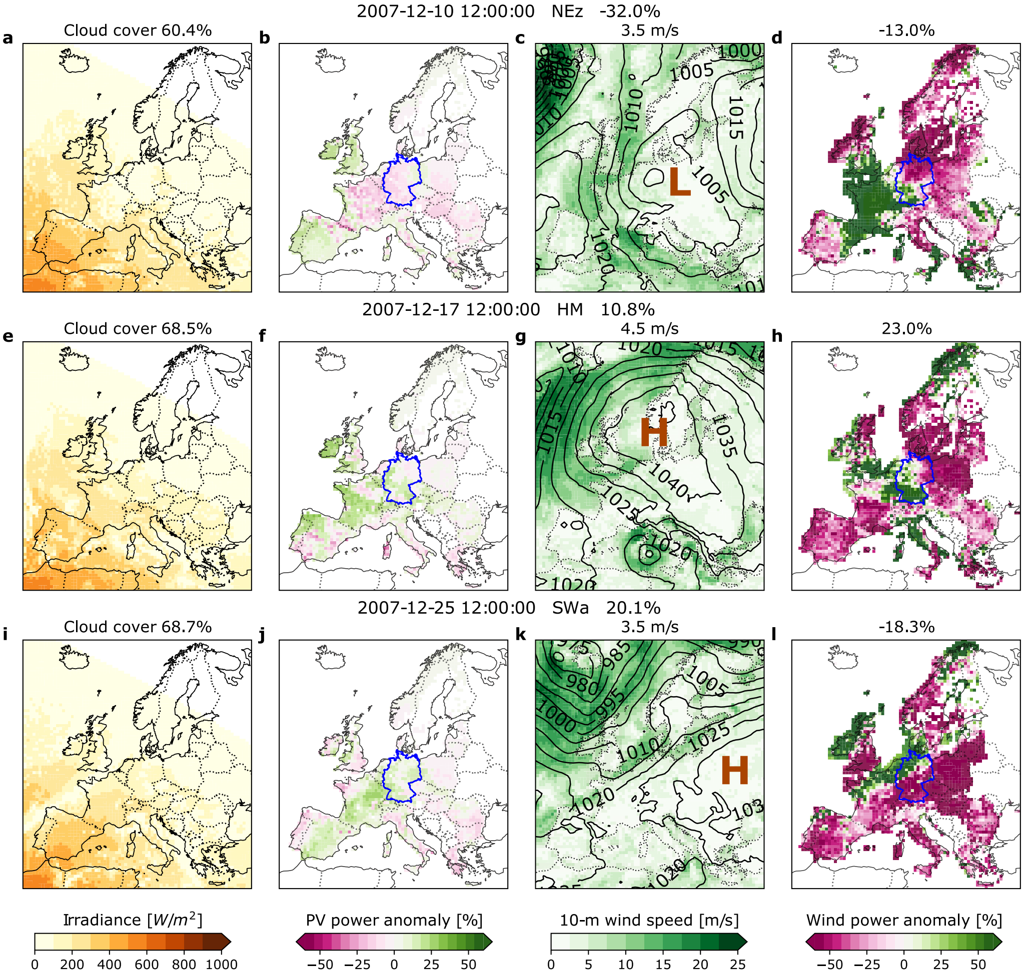


Fig. 6. Meteorological conditions in three selected times during the winter event December 2007 marked by dotted lines in Fig. 5. Four columns show (left to right) surface irradiance (%, shaded), anomalies of PV power production (%), wind speed at 10 m (shaded) with mean sea level pressure (contour), and anomalies of wind power onshore production (%). The numbers shown on top of the first-column panels are mean cloud cover (%) for Germany. The other numbers show the corresponding mean values for Germany. The title for each row shows the weather patterns and the anomalies of total power production of Germany at 12:00 on that day. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conditions associated with the low-pressure system reduced the PV power production across Germany below average and dampened the effect of increased wind power production on May 30, thus the total production was still below average in scenario-2050. In the following days, the low-pressure system moved westward and dissolved on June 4, again reducing the wind power production in Germany leading to the continuation of the prolonged low production event (Fig. 7).

The extreme event ended on June 4, when a high-pressure system formed over Iceland with a ridge extending over Central Europe (HNa), resulting in reduced cloudiness (53%) and increased surface irradiance. PV power increased accordingly, starting from northern Germany on June 5 (Fig. 8j) and affecting the entire country until June 10. Wind power production remained nevertheless relatively low during this period with anomalies of up to −22% on June 7.

4. Discussion

The regional differences in power production anomalies have implications for the future possibility of the transmission and storage of electricity. The direction of a pressure system development influences the spatial distribution of power production anomalies in Germany and the neighboring countries, here shown with the example of France and Denmark. The winter event in December 2007 (and the start of the May 2016 event) began with a high (low) pressure system forming over the North Atlantic in the northwest of Germany. In both cases, the pressure systems moved southeastward to Germany before continuing eastward over land and eventually dissolved. Following these developments, the negative anomalies of wind (PV) power production initiated in the northwest of Germany first, then expanding to Denmark, while France maintained an average power production in these cases (Fig. 5g and 7b). The tempo-spatial development of the power production anomalies poses a challenge since the west of Germany has industrial areas with high electricity demand and storage [40]. The North–South electricity transmission would be less useful in this case, particularly when wind power production in the North Sea and Denmark is simultaneously below average (Fig. 5g, 6d,h). Instead, the West-East electricity transmission line between France and Germany would be more helpful in balancing the extremes in power production.

In contrast, the Cut-off low-pressure system (TM) from May 29 to June 3, 2016, moved from the southwest to Germany. Negative anomalies of PV power production initiated in the south of Germany and France, while wind speeds increased in Denmark in the north of the Cut-off Low. Consequently, from May 29 to June 5, Germany and France had similar negative anomalies in total production, while Denmark had positive anomalies due to high wind power production on May 30 before returning to the climatological mean. In such situations, the North–South electricity transmission lines in Germany could be beneficial by importing surplus electricity from Denmark to the regions with electricity shortages in the south.

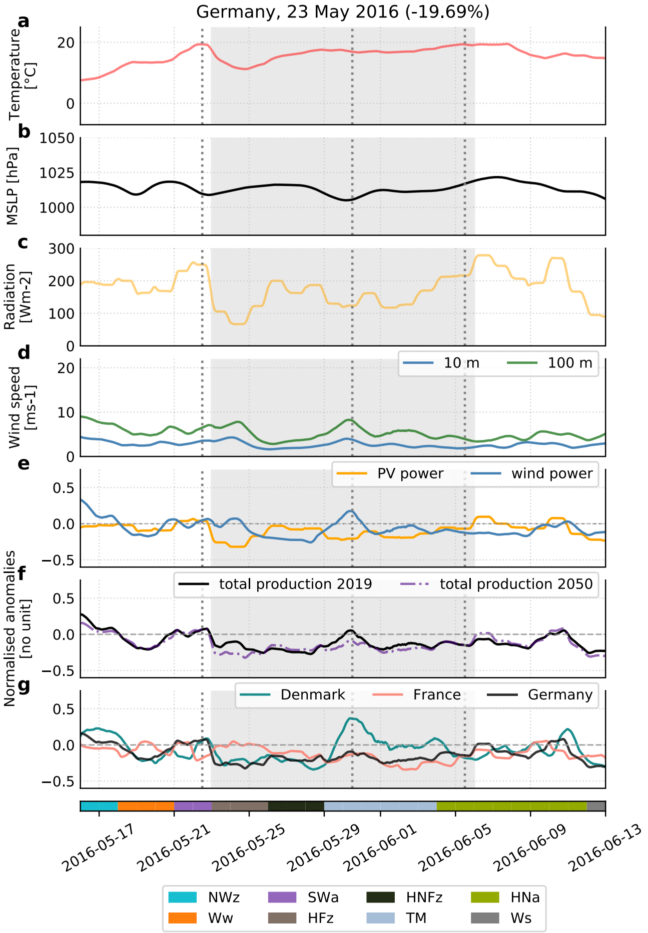


Fig. 7. Meteorological progression during a low production event in May 2016. Similar to Fig. 5 but for 14-day low production event in the summer, May 2016 (May 23 to June 5). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Interestingly, amongst 20 extreme events in Fig. 4, the winter event in Dec 2004 characterized the pattern HM from Dec 4–6, similar to the event in Dec 2007, but the low pressure system north of Great Britain moved southeastward made the North–South transmission lines from Denmark to Germany more beneficial (Supplementary Fig. S7a–d). On the contrary, the summer event in May 2007 characterized TM on May 30 to June 1, similar to the event in May 2016, but the low pressure system formed in France moved northeastward made the West-East transmission line from France to Germany more beneficial (Supplementary Fig. S7e–h). Nevertheless, the other 16 events did not include similar weather development and therefore, it is difficult to draw a definite conclusion. More studies with a larger number of events and weather conditions are thus required to understand the relationship between weather development and the role of transmission lines.

The total production in scenario-2050 may experience an alleviation of extremely low power production intensity during winter events but an exacerbation during summer events, relative to scale-2019. Over the 14 days of the winter event in December 2007, the anomalies of total production in scenario-2050 were moderate (closer to zero) compared to scale-2019 (Fig. 5). This stands in contrast to the summer event May 2016, where the total production in scenario-2050 has lower anomalous values than in scale-2019 due to the stronger impact from reduced PV power production on May 25 and 30 (Fig. 7). The need for battery storage during low production events in summer therefore increases in the future, as inflow for pumped storage is projected to decrease in summer due to reduced Alpine snow melt in future climate change [41]. This may be especially critical for the electricity provision since blocking high-pressure systems in summer may coincide with the development of heat waves. Heat waves can lead to an increase in the electricity demand for cooling during such low-power production episodes, and both the frequency and intensity of heat waves are projected to further increase with future global warming [18].

A notable observation is that the anomalies of total production did not remain consistently low throughout the entire 14-day low power production events. There were instances where wind speeds recovered to near or slightly above the climatological mean in the middle of the assessed events, such as around December 18, 2007, and May 30, 2016 (Fig. 5, 7). Similarly short increases in total production can be seen in other 14-day low production events for each season in Supplementary Fig. S5 and S6. However, these temporary increases in total production anomalies rarely exceed 10% above the climatological means, indicating that electricity shortages could be alleviated but not fully recovered. Two exceptions are in December 1996 and May 2007 with positive anomalies of up to 20%. The variations in total production during these events underscore the need to monitor weather conditions to prepare electricity storage for an extended period of low power production, even when the total production appears to recover briefly. Including more offshore wind power would enhance the effect of wind power. Therefore during these short recovery time from low wind speeds, the total production might more quickly increase and reach regional values that exceed the average total production values, which would allow to store or transmit the surplus electricity to alleviate low production days elsewhere.

5. Conclusion

We present a comprehensive comparison of extreme events for PV and wind power production in winter and summer in Germany. To that end, we simulated PV and wind power using present-day and future installations, defined with an increased ratio of PV to wind power installed capacity from 0.7:1 for the present-day installation (scaled-2019) to 2:1 for the future installation (scenario-2050) in Europe, which corresponds to an increase from 1:1 to 2.5:1 in Germany. We identified extreme anomalies in power production and compared the meteorological conditions associated with these extreme events using synoptic weather pattern classification with 29 patterns [19] for Germany.

The results show distinct characteristics in weather patterns associated with the lowest and highest total production events. High production events are predominantly associated with cyclonic weather patterns with 77% and 68% for present-day and 2050 installations, respectively. In particular, Cylonic Westerly (Wz) and Cyclonic North-Westerly (NWz) account for half of the days with high production events with a total of 51% in present-day installation. The seasonal differences in high-production events show no clear dependence on the installations, suggesting that conclusions for future high-production events can be drawn from results with present-day installations. In contrast, low production events are mainly associated with anticyclonic weather patterns with 63% in the present-day installation and are more influenced by an increased share of PV power installation. With the simulated future installation, low production events occur almost equally frequently with anticyclonic (53%) and cyclonic weather patterns (47%). This is due to the increase in the frequency of low production events occurring in summer associated with cyclonic patterns, driven by the higher influence of anomalously low PV power production on the total production.

Our analysis indicates an increased likelihood of extremely low production occurring in summer, rising from 5% to 25% of the total of 150 extreme events when we go from the present-day to the 2050 installation. In addition, the 14-day summer event in May 2016 shows lower anomalies in total production in the future installation compared to the present-day installation, indicating a potential exacerbation of

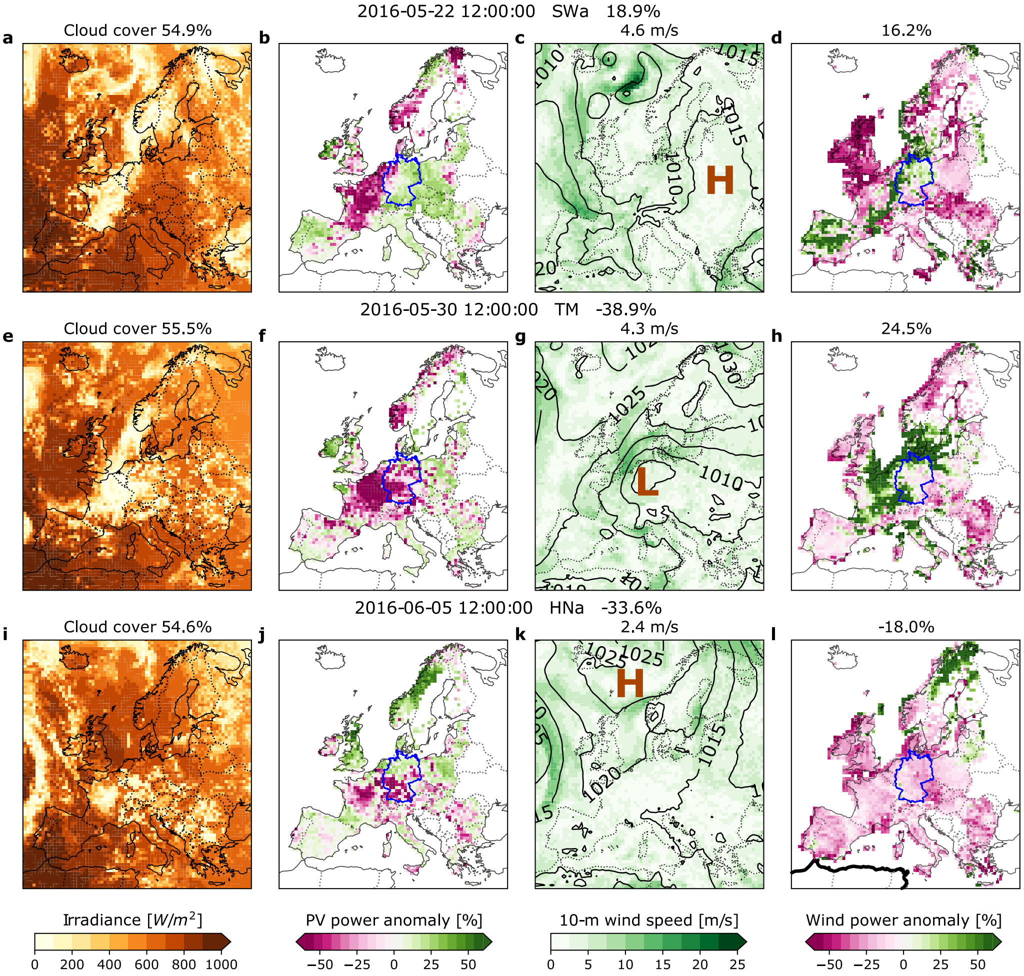


Fig. 8. Meteorological conditions in three selected times during low production event in May 2016. Similar to Fig. 6 but for the summer event May 2016 at three times marked in dotted lines in Fig. 7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extremely low production events in summer in the future. With climate change, the peak demand for cooling in summer will define the annual maximum load in Germany by 2100 [41]. The combination of low power production and high electricity demand in summer can therefore pose extra stress on the energy supply system.

There are distinct differences between the 14-day low-production events in winter and summer. In terms of the magnitude of anomalies, summer events have relatively low PV and wind power production, with a lowest PV power anomaly of −15% and a lowest wind power anomaly of −19%. In contrast, during winter events, PV power produces slightly below the climatological mean up to −9%, while wind power produces much lower amounts with anomalies up to −37%. In terms of meteorological conditions, the majority (13 of 20) of 14-day lowest production events are associated with stationary weather patterns that lasted at least five days, with stationary anticyclonic patterns being more prevalent in winter events, while stationary cyclonic patterns being more prevalent in summer events. There are no repeating sequences of weather patterns during these prolonged low production events; rather, the extremely negative anomalies come from combinations of several patterns with low PV and/or low wind power production. There are great uncertainties on how stationary cyclonic and anticyclonic conditions vary with climate change in terms of frequency, intensity, and duration [42,43]. How future changes in stationary weather patterns can affect prolonged low-production events can be explored in future studies. There is an increased persistence of weather patterns compared in the 20th century (since 1881), especially in the 1970s-80s [44]. However, for climate projections in the future, studies show high uncertainty on how atmospheric blockings might change due to differences in definition and in representation in numerical weather prediction models [43]. While the frequency and duration of atmospheric blockings might decrease [42,43], rare but high impact blockings such as those with extremely high intensity (strong pressure gradient) and long duration are possible [43]. The implication thus differs for the statistical 20 most extreme events and for the most extreme events, i.e., the overall number of low-power production events might decrease, but the most extreme low-wind power production events would be intensified in terms of duration and severity.

How these weather systems move during these events influences which transmission lines between Germany and neighboring countries Germany could be more helpful in electricity shortage. Our case studies indicate that both North–South and West-East transmission lines are needed during production shortfalls in Germany due to the different propagation directions of the production anomalies during the developments of different weather conditions.

Our findings highlighted that extreme events in PV and wind power production, especially low power production events, may become more frequent and more severe in summer for a plausible future power installations in Germany. The results provide first insights for planning the future energy system. To support the energy transition, future studies need to explore extreme events in renewable power production with additional simulations of the electricity demand and storage, such as from hydropower and batteries, and the electricity transmission from neighboring countries in Europe and elsewhere. To do so, more plausible future projections for PV and wind power production sites are needed, since gridded data for installations are scarce and currently hinder the advancement of the understanding of weather impacts on renewable power systems.

CRediT authorship contribution statement

Linh Ho-Tran: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stephanie Fiedler:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The CLIMIX data was acquired from the author [14]. The code of the Renewable Energy Model (REM) is available at [45]. The data of REM are available at https://www.wdc-climate.de/ui/entry{a}cronym=DKRZ_LTA_1198_ds00003.

Acknowledgments

This study has been conducted in the framework of the Hans-Ertel-Centre for Weather Research funded by the German Federal Ministry for Transportation and Digital Infrastructure, Germany (grant number BMVI/DWD 4818DWDP5A). We thank the German Weather Service for providing COSMO-REA6 data, P. James for the data for the weather patterns, C. Frank for the code for photovoltaic power simulations, and S. Jerez for the CLIMIX data.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.solener.2024.112979.

References

[1] European Commission, European green deal : delivering on our targets, 2021, Directorate-General for Communication, https://data.europa.eu/doi/10.2775/373022, (Accessed: 2023-03-21).

[2] BMBF, Federal Ministry of Education and Research, German energy transition, 2019, URL https://www.bmbf.de/bmbf/en/research/energy-and-economy/german-energy-transition/german-energy-transition_node.html. (Accessed: 2023-08-07).

[3] Umweltbundesamt, Energy target 2050: 100% renewable electricity supply, 2010, https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/energieziel_2050_kurz.pdf, (Accessed: 2023-04-12).

[4] BMWK, Bundesministerium für Wirtschaft und Klimaschutz, Entwicklung der erneuerbaren Energien in Deutschland im Jahr 2022, 2023, URL https://www.erneuerbare-energien.de/EE/Navigation/DE/Service/Erneuerbare_Energien_in_Zahlen/Entwicklung/entwicklung-der-erneuerbaren-energien-in-deutschland.html. (Accessed: 2023-08-07).

[5] ISE, Net electricity generation in Germany in 2022: Significant increase in generation from wind and PV, 2023, Press Release https://www.ise.fraunhofer.de/en/press-media/press-releases/2023/net-electricity-generation-in-germany-in-2022-significant-increase-in-generation-from-wind-and-pv.html, (Accessed: 2023-04-12).

[6] Energy-Charts, Installierte Netto-Leistung zur Stromerzeugung in Deutschland in 2022, 2022, URL https://energy-charts.info/charts/installed_power/chart.htm?l=de&c=DE&chartColumnSorting=default&year=2022. (Accessed: 2023-08-07).

[7] K. van der Wiel, L.P. Stoop, B. Van Zuijlen, R. Blackport, M. Van den Broek, F. Selten, Meteorological conditions leading to extreme low variable renewable energy production and extreme high energy shortfall, Renew. Sustain. Energy Rev. 111 (2019) 261–275.

[8] B. Burger, Öffentliche Nettostromerzeugung in Deutschland im Jahr 2022, 2023, Presentation https://www.energy-charts.info/downloads/Stromerzeugung_2022.pdf, (Accessed: 2023-04-12).

[9] G.E.A. dena, Pumped-storage integrates renewable energy into the grid, 2015, URL https://www.dena.de/en/topics-projects/energy-systems/flexibility-and-storage/pumped-storage/. (Accessed: 2023-08-07).

[10] EWI (Energiewirtschaftliches Institut an der Universität zu Köln), dena pilot study “Towards climate neutrality”. Climate neutrality 2045 - Transformation of final energy consumption and the energy system, 2021, Published by the German Energy Agency GmbH (dena).

[11] C.M. Grams, R. Beerli, S. Pfenninger, I. Staffell, H. Wernli, Balancing Europe’s wind-power output through spatial deployment informed by weather regimes, Nat. Clim. Chang. 7 (8) (2017) 557–562.

[12] J. Drücke, M. Borsche, P. James, F. Kaspar, U. Pfeifroth, B. Ahrens, J. Trentmann, Climatological analysis of solar and wind energy in Germany using the Grosswetterlagen classification, Renew. Energy (2020).

[13] L. Ho-Tran, S. Fiedler, A climatology of weather-driven anomalies in European photovoltaic and wind power production, Commun. Earth Environ. 5 (1) (2024) 63.

[14] S. Jerez, F. Thais, I. Tobin, M. Wild, A. Colette, P. Yiou, R. Vautard, The CLIMIX model: a tool to create and evaluate spatially-resolved scenarios of photovoltaic and wind power development, Renew. Sustain. Energy Rev. 42 (2015) 1–15.

[15] Eurostat, Eurostat renewable energy statistics, 2020, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics#Share_of_renewable_energy_more_than_doubled_between_2004_and_2020. (Accessed: 2022-04-14).

[16] J. Wohland, D. Brayshaw, S. Pfenninger, Mitigating a century of European renewable variability with transmission and informed siting, Environ. Res. Lett. 16 (6) (2021) 064026.

[17] S. Perkins, L. Alexander, J. Nairn, Increasing frequency, intensity and duration of observed global heatwaves and warm spells, Geophys. Res. Lett. 39 (20) (2012).

[18] V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. Gomis, et al., Climate change 2021: the physical science basis, Contrib. Work. Group I Sixth Assess. Rep. Intergov. Panel Clim. Chang. 2 (1) (2021) 2391.

[19] P. James, An objective classification method for Hess and Brezowsky Grosswetterlagen over Europe, Theor. Appl. Climatol. 88 (1–2) (2007) 17–42.

[20] C. Bollmeyer, J. Keller, C. Ohlwein, S. Wahl, S. Crewell, P. Friederichs, A. Hense, J. Keune, S. Kneifel, I. Pscheidt, et al., Towards a high-resolution regional reanalysis for the European CORDEX domain, Q. J. R. Meteorol. Soc. 141 (686) (2015) 1–15.

[21] S. Pfenninger, I. Staffell, Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data, Energy 114 (2016) 1251–1265.

[22] I. Staffell, S. Pfenninger, Using bias-corrected reanalysis to simulate current and future wind power output, Energy 114 (2016) 1224–1239.

[23] L. Dubus, Y.-M. Saint-Drenan, A. Troccoli, M. De Felice, Y. Moreau, L. Ho-Tran, C. Goodess, L. Sanger, C3S energy: A climate service for the provision of power supply and demand indicators for Europe based on the ERA5 reanalysis and ENTSO-E data, Meteorol. Appl. 30 (2023) e2145.

[24] T. Huld, G. Friesen, A. Skoczek, R.P. Kenny, T. Sample, M. Field, E.D. Dunlop, A power-rating model for crystalline silicon PV modules, Sol. Energy Mater. Sol. Cells 95 (12) (2011) 3359–3369.

[25] C.W. Frank, S. Wahl, J.D. Keller, B. Pospichal, A. Hense, S. Crewell, Bias correction of a novel European reanalysis data set for solar energy applications, Sol. Energy 164 (2018) 12–24.

[26] Y.-M. Saint-Drenan, L. Wald, T. Ranchin, L. Dubus, A. Troccoli, An approach for the estimation of the aggregated photovoltaic power generated in several European countries from meteorological data, Adv. Sci. Res. 15 (2018) 51–62.

[27] European Commission, Joint Research Centre (JRC), Global energy and climate outlook 2020: Energy, greenhouse gas and air pollutant emissions balances, 2020, *Dataset* https://data.jrc.ec.europa.eu/dataset/1750427d-afd9-4a10-8c54-440e764499e4. (Accessed: 2022-04-24).

[28] K. van der Wiel, H.C. Bloomfield, R.W. Lee, L.P. Stoop, R. Blackport, J.A. Screen, F.M. Selten, The influence of weather regimes on European renewable energy production and demand, Environ. Res. Lett. 14 (9) (2019) 094010.

[29] I. Tobin, S. Jerez, R. Vautard, F. Thais, E. Van Meijgaard, A. Prein, M. Déqué, S. Kotlarski, C.F. Maule, G. Nikulin, et al., Climate change impacts on the power generation potential of a European mid-century wind farms scenario, Environ. Res. Lett. 11 (3) (2016) 034013.

[30] I. Tobin, W. Greuell, S. Jerez, F. Ludwig, R. Vautard, M. Van Vliet, F. Breón, Vulnerabilities and resilience of European power generation to 1.5 C, 2 C and 3 C warming, Environ. Res. Lett. 13 (4) (2018) 044024.

[31] W. Zappa, M. Van Den Broek, Analysing the potential of integrating wind and solar power in Europe using spatial optimisation under various scenarios, Renew. Sustain. Energy Rev. 94 (2018) 1192–1216.

[32] R. Vautard, F. Thais, I. Tobin, F.-M. Bréon, J.-g.D. De Lavergne, A. Colette, P. Yiou, P.M. Ruti, Regional climate model simulations indicate limited climatic impacts by operational and planned european wind farms, Nature communications 5 (1) (2014) 3196.

[33] GISCO: Geographical Information and Maps, EuroGeographics for the administrative boundaries, 2020, https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units. (Accessed: 2020-03-23).

[34] T. Klaus, C. Vollmer, K. Lehmann, K. Müschen, R. Albert, M. Bade, T. Charissé, F. Eckermann, R. Herbener, U. Kaulfersch, G. Knoche, K. Kuhnhenn, C. Lohse, C. Loreck, U. Lorenz, B. Lünenbürger, M. Memmler, C. Mordziol, A. Ostermeier, B. Westermann, 2050 Energy Target: 100% Renewable Electricity Supply, Umweltbundesamt, 2010.

[35] O. Ruhnau, S. Qvist, Storage requirements in a 100% renewable electricity system: extreme events and inter-annual variability, Environ. Res. Lett. 17 (4) (2022) 044018.

[36] P. Zschenderlein, G. Fragkoulidis, A.H. Fink, V. Wirth, Large-scale Rossby wave and synoptic-scale dynamic analyses of the unusually late 2016 heatwave over Europe, Weather 73 (9) (2018) 275–283.

[37] M. Röthlisberger, L. Frossard, L.F. Bosart, D. Keyser, O. Martius, Recurrent synoptic-scale rossby wave patterns and their effect on the persistence of cold and hot spells, J. Clim. 32 (11) (2019) 3207–3226.

[38] D. Barriopedro, R. García-Herrera, A.R. Lupo, E. Hernández, A climatology of northern hemisphere blocking, J. Clim. 19 (6) (2006) 1042–1063.

[39] L.-A. Kautz, O. Martius, S. Pfahl, J.G. Pinto, A.M. Ramos, P.M. Sousa, T. Woollings, Atmospheric blocking and weather extremes over the Euro-Atlantic sector–a review, Weather Clim. Dyn. 3 (1) (2022) 305–336.

[40] J. Figgener, C. Hecht, D. Haberschusz, J. Bors, K.G. Spreuer, K.-P. Kairies, P. Stenzel, D.U. Sauer, The development of battery storage systems in Germany: A market review, 2023, https://battery-charts.rwth-aachen.de/.

[41] G. Totschnig, R. Hirner, A. Müller, L. Kranzl, M. Hummel, H.-P. Nachtnebel, P. Stanzel, I. Schicker, H. Formayer, Climate change impact and resilience in the electricity sector: the example of Austria and Germany, Energy Policy 103 (2017) 238–248.

[42] T. Shaw, M. Baldwin, E.A. Barnes, R. Caballero, C. Garfinkel, Y.-T. Hwang, C. Li, P. O'gorman, G. Rivière, I. Simpson, et al., Storm track processes and the opposing influences of climate change, Nat. Geosci. 9 (9) (2016) 656–664.

[43] T. Woollings, D. Barriopedro, J. Methven, S.-W. Son, O. Martius, B. Harvey, J. Sillmann, A.R. Lupo, S. Seneviratne, Blocking and its response to climate change, Curr. Clim. Chan. Rep. 4 (3) (2018) 287–300.

[44] J. Kyselỳ, P. Domonkos, Recent increase in persistence of atmospheric circulation over europe: comparison with long-term variations since 1881, Int. J. Climatol. 26 (4) (2006) 461–483.

[45] L. Ho, S. Fiedler, S. Wahl, PV and Wind Power Dataset for Europe, 2023, URL https://www.wdc-climate.de/ui/entry?acronym=DKRZ_LTA_1198_ds00003.